BRITISH COLUMBIA
ACID MINE DRAINAGE
TASK FORCE

Canada

BC

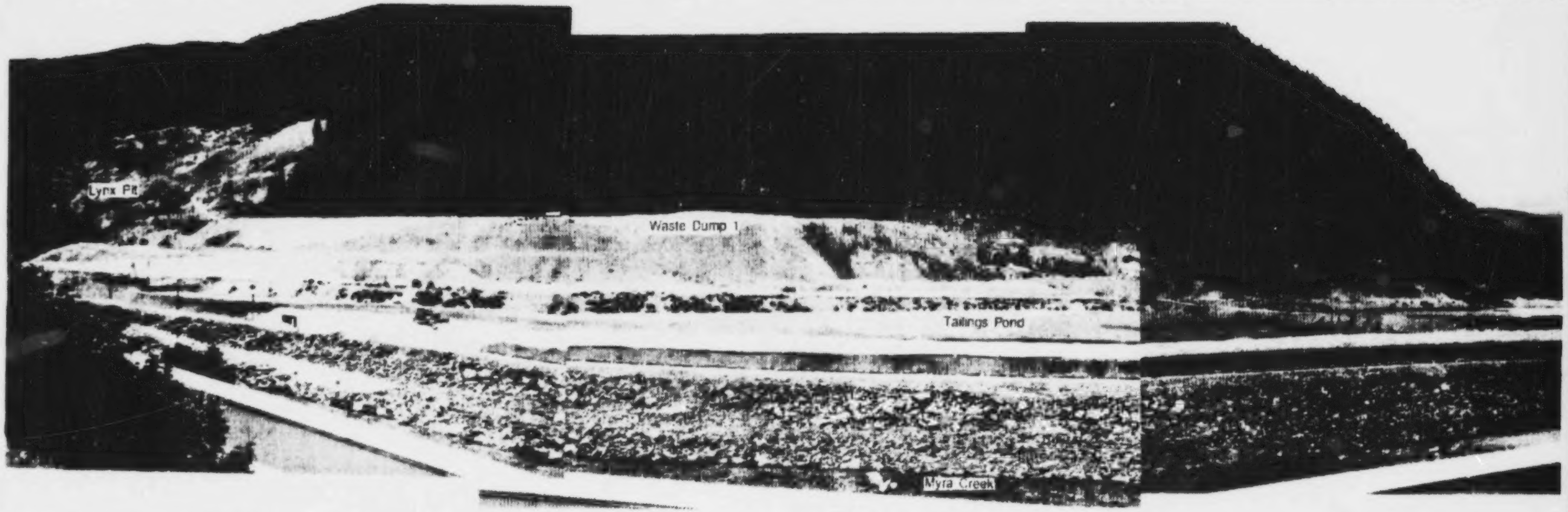
HYDROGEOLOGICAL ASSESSMENT
AND DEVELOPMENT
OF AMD CONTROL TECHNOLOGY
FOR MYRA FALLS WASTE ROCK

Dennis Konasewich
Carol Jones
Kevin Morin
Eva Gerencher

Northwest Geochem
#204 - 26 Bastion Square,
Victoria, B.C. V8W 1H9

September, 1990

This project was funded by Energy, Mines and Resources Canada and the British Columbia Ministry of Energy, Mines and Petroleum Resources under the Canada/British Columbia Mineral Development Agreement; and by Westmin Resources Limited.


Lynx Pit
Waste Dump 1
Tailings Pond
Myra Creek

MYRA FALLS WASTE ROCK DUMP STUDY AREA

TABLE OF CONTENTS

Executive Summary v

1.0 INTRODUCTION 1

2.0 PHYSICAL AND CHEMICAL HYDROGEOLOGY OF THE WESTMIN WASTE ROCK DUMP 4

- 2.1 Introduction 4
- 2.2 Previous Studies 6
- 2.3 Physical Hydrogeology 12
  - *2.3.1 Stratigraphy* 15
  - *2.3.2 Groundwater Movement* 19
- 2.4 Chemical Hydrogeology 22
  - *2.4.1 Acid Generation, Migration and Neutralization* 23
  - *2.4.2 Laboratory Tests of Acid Generation* 30
- 2.5 Impact of Acid Generation on Water Quality 34
- 2.6 Conclusion 45

3.0 CONTROL OPTIONS FOR AMD AT WESTMIN 47

4.0 BACTERICIDE EVALUATION 49
- 4.1 Experimental Procedures 49
- 4.2 Results and Conclusions 50

5.0 SOLIDIFICATION 55
- 5.1 Laboratory Studies - Procedures 56
- 5.2 Preliminary Studies: Solidification of Wastewater Sludges 64
- 5.3 Optimization of Cementitious Mixtures 71
  - *5.3.1 Water - Cement Ratio* 73
  - *5.3.2 Cement Content* 73
  - *5.3.3 Effect of Aggregate Particle Size and Distribution* 73
  - *5.3.4 Effect of Admixtures* 75
  - *5.3.5 Effect of Additions of Supplementary Cementing Materials* 83
  - *5.3.6 Chemical Characteristics* 89
  - *5.3.7 Cost Comparison* 89

6.0 FIELD STUDIES 93
- 6.1 Procedure 93
- 6.2 Results 93
  - *6.2.1 Structural Integrity* 96
  - *6.2.2 Chemical Integrity of Solidified Mixtures* 97
- 6.3 Future Studies 98

7.0 GROUTING 101

8.0 CONCLUSIONS 103

References 105

Appendix

LIST OF FIGURES

1.1 Site Plan 2

1.2 Research Approach for AMD Control at Westmin Resources Ltd. 3

2.1 Schematic diagram of Waste Rock Dump #1 at Westmin's Myra Falls Minesite 5

2.2 Surface water quality sites in the vicinity of Myra Falls (after B.C. Research, 1981) 7

2.3 Aqueous pH vs time for pit drainage (Station M6) and surface seeps on the northeast side (M11) and southside (M15) of the waste rock dump 8

2.4 Aqueous pH vs time for piezometers drilled through the toe of the dump (S10) into underlying sediments 10

2.5 Borehole locations and surface elevations at the waste rock dump 13

2.6 Conceptual model of water movement in and around the waste rock dump 14

2.7 Elevation of original land surface at the waste rock dump 16

2.8 Thickness of the organic layer beneath the waste rock dump 17

2.9 Thickness of the waste rock within the dump 18

2.10 Water table elevation in and beneath the dump. An approximate value (error less than 4m) has been inserted at 45-1 for orientation of contour lines 20

2.11 Results of acid-base accounting for Borehole 26 26

2.12 Results of acid-base accounting for Borehole 15 28

2.13 Results of acid-base accounting for Borehole 20 29

2.14 Effluent pH and rate of acidity production from Columns 1 through 4 31

2.15 Effluent pH and rate of acidity production from Columns 5 and 6 and the humidity cell 2. 32

2.16 Effluent pH and rate of acidity production from Columns 8 and the corresponding humidity cell. 35

2.17 Sulfate vs pH for groundwater samples (1988, 1989 data) 37

2.18 Zinc vs pH for groundwater samples (1988, 1989 data) 38

2.19 Zinc vs sulfate for groundwater samples (1988, 1989 data) 39

LIST OF FIGURES (Cont'd)

2.20 Alkalinity vs pH in groundwater (1988, 1989 data) 41

2.21 Spatial trends in groundwater pH in 1988 and 1989 43

2.22 Spatial trends in groundwater chemistry in November 1989 44

4.1 Effect of surfactant (WSCP) treatment on acidity column 1 vs control 51

4.2 Effect of surfactant (WSCP) treatment on acidity column 2 vs control 52

4.3 Effect of surfactant (WSCP) treatment on acidity column 3 vs control 53

4.4 Effect of surfactant (WSCP) treatment on acidity column 4 vs control 54

5.1 Approach used for solidification studies 57

5.2 Grain size distribution of Westmin coarse tailings 60

5.3 Grain size distribution of Westmin fine tailings 61

5.4 Comparison of Cement/Sludge Ratios 65

5.5 Comparison of Cement/Sludge Ratios Leachate Data 66

5.6 Comparison of Cement/Sludge/Shale Ratios 68

5.7 Comparison of Fine vs Coarse Tailings 69

5.8 Evaluation of Mixtures with and without Wastewater sludge 70

5.9 Water - Cement Ratio vs Strength 74

5.10 Strength and Initial Set Time as a Function of Cement Content 74

5.11 Fine and Coarse Tailings Addition - Effect on Initial Set Time 76

5.12 Effect of Particle Size Distribution on Set Time and Strength 77

5.13 Aggregate Addition vs 7 and 28 Day Strength 78

5.14 Additive Addition vs Strength 81

5.15 Additive Addition vs 7 and 28 Day Strength 82

5.16 Effect of Lime Addition on Set Time and Compressive Strength 85

5.17 Effect of Fly Ash on Set Time and Strength 87

5.18 Effect of Soluble Silicate on Set Time and Strength 88

5.19 Net Neutralization Potential of Cementitious Mixtures 90

LIST OF TABLES

TABLE

2.1 Summary of Acid-Base Accounting of Borehole Samples 24

2.2 Summary of ABA Trends in Boreholes 25

5.1 Elemental Analysis of Westmin Wastewater Sludge, Fine and Coarse Tailings 59

5.2 Freeze/Thaw Resistance of Mixtures Containing Admixtures 80

5.3 Effect of Sludge and Lime Additions on Setting Time and Strength Characteristics of Cementitious Mixtures 84

5.4 Cost Comparison of Mixtures Containing Supplementary Cementing Material 92

6.1 Results of Field Testing Program 95

6.2 Pre & Post Cover, Westmin Test Pile Data (mg/L) 99

PLATE

1 Application of Surface Sealant Mixture 94

EXECUTIVE SUMMARY

This report describes the studies which occurred during a three year program to assess acid generation and groundwater flow at the Westmin Myra Falls waste rock dump and to evaluate novel approaches for the prevention of acid mine drainage from the waste rock dump at the Westmin Myra Falls site.

The waste dump characterization indicated that the most active areas of oxidation occur within a 10 meter depth of exposed surfaces of the waste rock dump and in deeper zones where relatively high contents of sulfide minerals are encountered. During periods of significant rainfall, the shallow acid-generating zones are flushed with water and acidic water appears beneath the water table. Calculations suggest that a significant portion of the annual production of acidity is retained in the dump and therefore remains available for flushing. As a result, remediation and decommissioning planning must address the neutralization of this acidity or the control of infiltration and water-table variation.

Two acid mine drainage control approaches were evaluated; the use of alternative bactericides to reduce the activity of Thiobacillus ferrooxidans, and the use of solidified mine waste materials for the purpose of sealing waste rock to minimize moisture and air transfer and, hence hinder acid generation. The laboratory studies, and the results of the dump characterization study, suggested that a bactericidal approach would not be effective for control of acid mine drainage from the Westmin waste dump. Limitations include application techniques and the need to control acid formation at depth.

The study program then focused on the possible formation of a durable solidified material using mine waste materials such as wastewater sludges and mine tailings as principal components. The intent is to use the material as a surface sealant and/or grouting material to minimize water and air transfer in the waste rock dump. More than 105 test solidification mixtures were prepared and tested for properties such as strength, setting times, leaching and permeability. Five mixtures were selected for field application and testing on field waste rock piles. The leachates from the field test piles were monitored constantly for pH, and tested at intervals for water quality. The integrity of the solidified materials is observed at intervals and the results suggest that mixtures which can stand the "test of time" with respect to physical and chemical

integrity can be prepared for use as surface sealants. However, it must be recognized that the time-frame for this study was relatively limited. Mixtures for use as grouting materials have been prepared and tested on a field scale. Preliminary results suggest that the mixtures can be successfully used for grouting.

On the basis of laboratory and limited field scale studies, the approach of using solidified mine waste materials as a cover and grouting medium appears promising and further investigation of field application techniques should be pursued. Shotcreting appears to be the most promising means of covering the waste rock dump with the cementitious materials, and field trials are anticipated during 1990.

1.0 INTRODUCTION

Waste rock dumps at Westmin Resources Ltd., Myra Falls mine site contain sulphide minerals and generate acidic drainage with elevated metal loadings, particularly zinc, copper and cadmium. A water collection and treatment system is presently in place to protect the downstream environment but the reclamation of these dumps and the eventual decommissioning of the mine will require control of the acid generation. An assessment of the technology available in 1987 for such a control system indicated that a cost-effective, long term solution to this site acid generation was not available. In addition, hydrogeology and the acid generation at the Myra Falls mine site was not well understood.

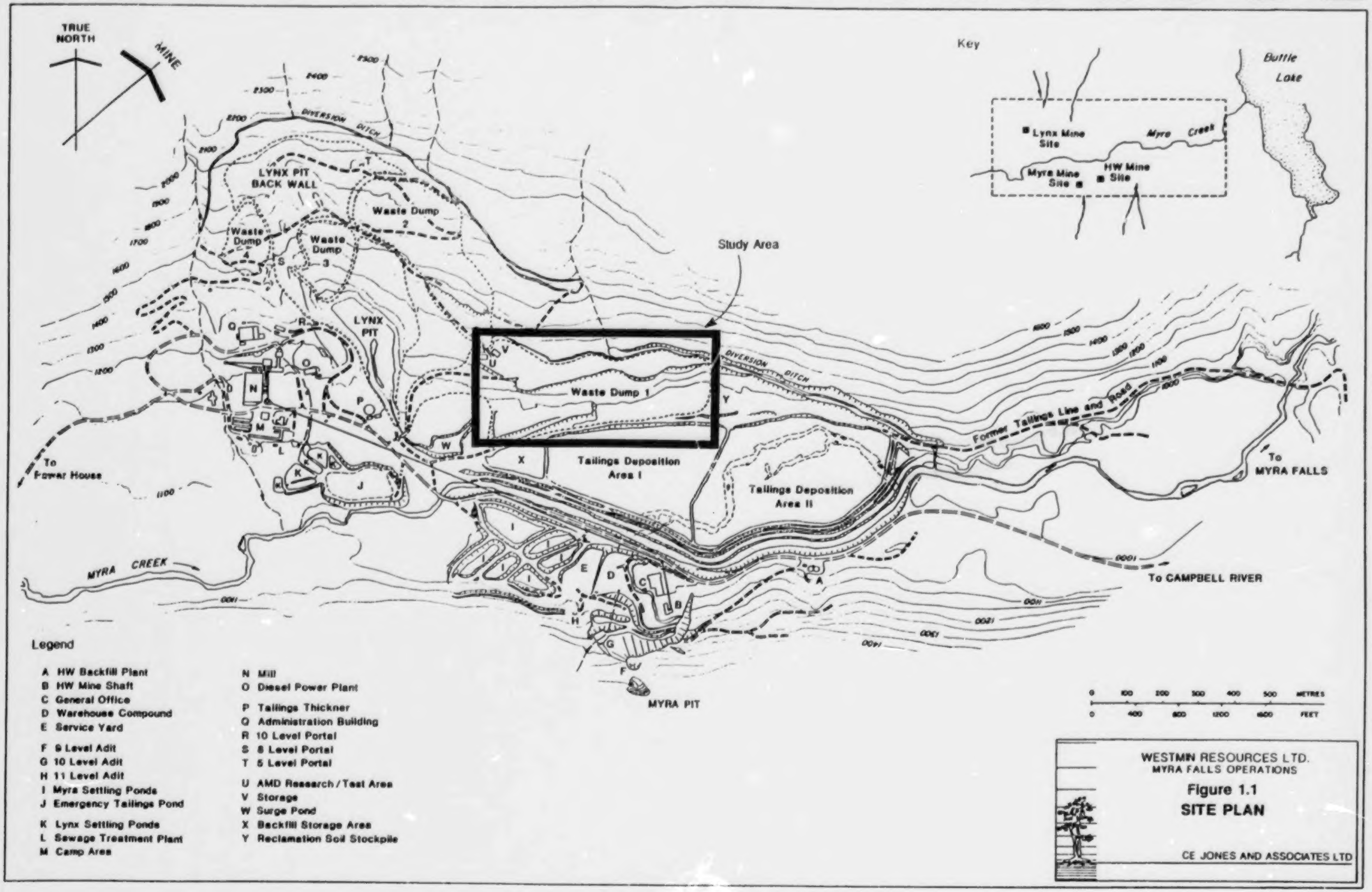
Therefore the objective of this research program was two-fold:

1. to characterize the acid drainage from the waste rock dumps, in particular to assess the hydrogeology of the main #1 dump (Site Plan, Figure 1.1)

2. to develop a cost-effective solution to control of acid generation in waste rock which would be compatible with final revegetation and decommissioning of the site.

The approach taken in this research program is illustrated in Figure 1.2. As evident from this flow chart the research program is not complete, however, major goals have been achieved in both the characterization of acid generation in the waste rock and in the development of a suitable control technology. This document provides a detailed assessment of the research efforts to date and describes the field scale testing which is proposed before the remediation strategy is finalized and waste dump treatment is begun.

This research program has been funded by Westmin Resources Ltd, and the Mineral Development Agreement assistance program.

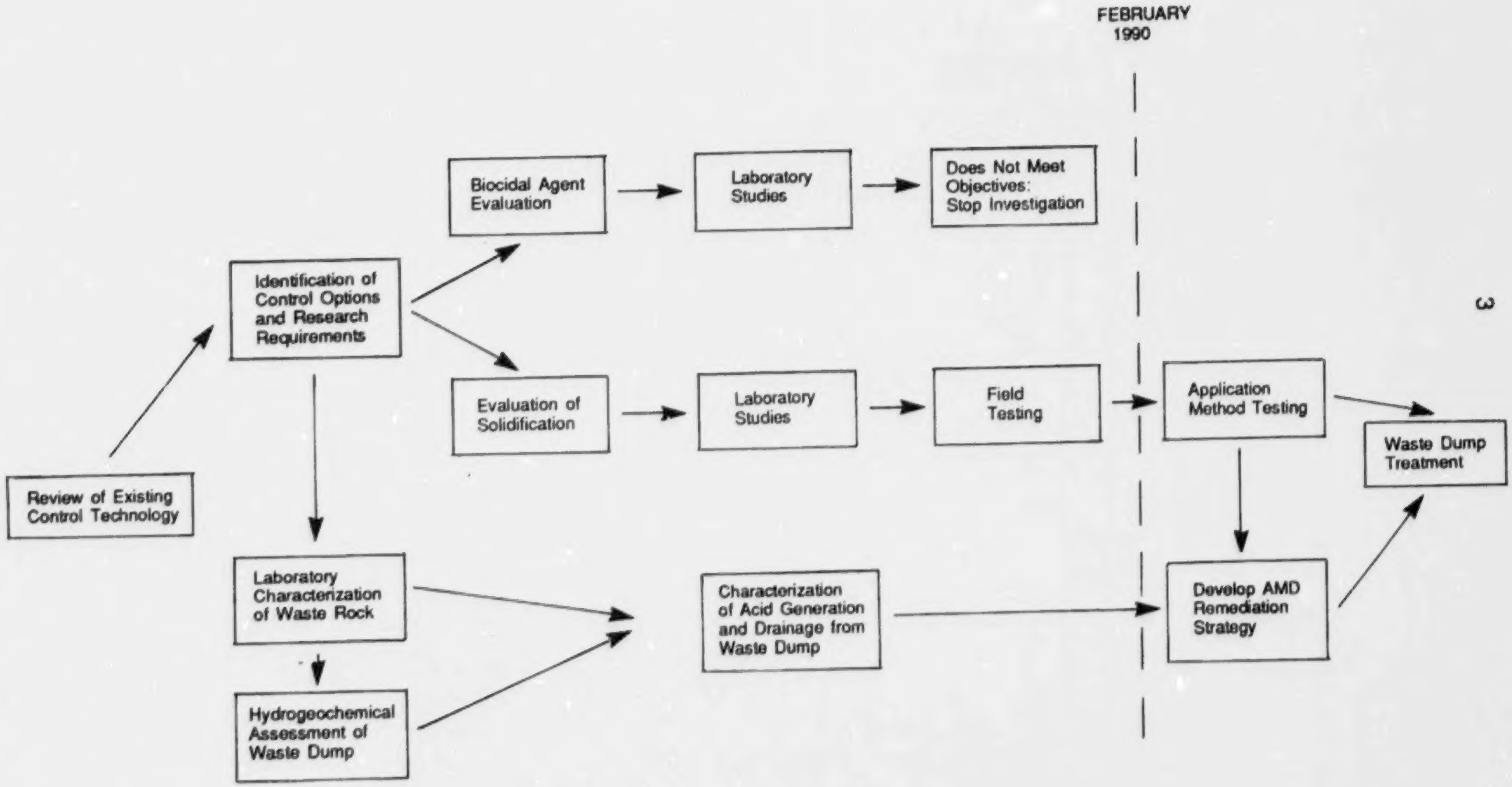

TRUE NORTH
MINE
Key
Buttle Lake
Lynx Mine Site
Myra Creek
Myra Mine Site
HW Mine Site
DIVERSION DITCH
LYNX PIT BACK WALL
Waste Dump 2
Waste Dump 4
Waste Dump 3
LYNX PIT
Study Area
Waste Dump 1
Tailings Deposition Area I
Tailings Deposition Area II
Former Tailings Line and Road
To MYRA FALLS
To CAMPBELL RIVER
To Power House
MYRA CREEK
MYRA PIT
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Legend
A HW Backfill Plant
B HW Mine Shaft
C General Office
D Warehouse Compound
E Service Yard
F 9 Level Adit
G 10 Level Adit
H 11 Level Adit
I Myra Settling Ponds
J Emergency Tailings Pond
K Lynx Settling Ponds
L Sewage Treatment Plant
M Camp Area
N Mill
O Diesel Power Plant
P Tailings Thickner
Q Administration Building
R 10 Level Portal
S 8 Level Portal
T 5 Level Portal
U AMD Research / Test Area
V Storage
W Surge Pond
X Backfill Storage Area
Y Reclamation Soil Stockpile
0 100 200 300 400 500 METRES
0 400 800 1200 1600 FEET

WESTMIN RESOURCES LTD.
MYRA FALLS OPERATIONS

Figure 1.1
SITE PLAN

CE JONES AND ASSOCIATES LTD

Figure 1.2
Research Approach for AMD Control at Westmin Resources Ltd., Myra Falls Operation


FEBRUARY 1990
Review of Existing Control Technology
Identification of Control Options and Research Requirements
Biocidal Agent Evaluation
Laboratory Studies
Does Not Meet Objectives: Stop Investigation
Evaluation of Solidification
Laboratory Studies
Field Testing
Application Method Testing
Waste Dump Treatment
Laboratory Characterization of Waste Rock
Hydrogeochemical Assessment of Waste Dump
Characterization of Acid Generation and Drainage from Waste Dump
Develop AMD Remediation Strategy

2.0 PHYSICAL AND CHEMICAL HYDROGEOLOGY OF THE WESTMIN WASTE ROCK DUMP

2.1 Introduction

The Westmin Myra Falls minesite is located in a relatively narrow and steep valley in the central region of Vancouver Island, British Columbia. The valley is oriented east-west relative to true north and north-northeast relative to mine north. The mining operations have consisted of underground galleries in both walls of the valley as well as an open pit (Lynx Pit) excavated into the north valley wall. Most of the waste rock from the operation has been placed in dumps constructed along the north valley wall, just east of the inactive pit. The largest dump is known as Dump #1; however, many of the dumps are laterally adjacent so that the distinctions among them are not thought to be critical at this time.

Prior to waste-rock dumping, the north valley wall in the area generally had a slope of 16° from horizontal (approximately 3 horizontal:1 vertical). In places, the surface slope was somewhat steeper or shallower than the average, but consistently decreased in elevation to the relatively flat Myra Creek floodplain. Beneath the western side of the present dump area, a creek channel and/or swamp existed on the floodplain.

The waste rock was placed in lifts on the valley floor against the valley wall (Figure 2.1). This resulted in a dump with a measured thickness of up to 42 meters in the center of the dump, decreasing in thickness away from the center towards the upper valley wall and towards the toe adjacent to the current tailings area in the center of the valley.

This section presents the evaluation of the physical and chemical hydrogeology of the Westmin dump based on data gathered through the years of 1981-1989. Physical hydrogeology as used in this report refers to the physical movement of water through the dump and the underlying rock and sediments. Chemical hydrogeology encompasses the generation of acid within the waste rock, the migration of the acidity relative to groundwater movement, and the impact of the acidity and metal leaching on water quality throughout the dump and the surrounding strata.

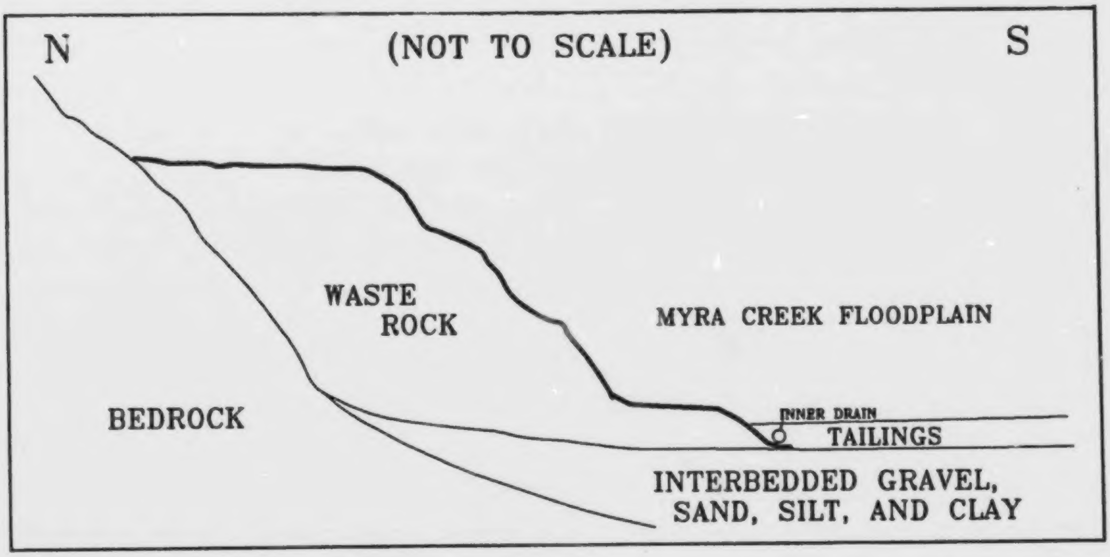

N
(NOT TO SCALE)
S
WASTE ROCK
MYRA CREEK FLOODPLAIN
BEDROCK
INNER DRAIN
TAILINGS
INTERBEDDED GRAVEL, SAND, SILT, AND CLAY

Figure 2.1 Schematic diagram of Waste Rock Dump #1 at Westmin's Myra Falls Minesite.

2.2 Previous Studies

In early 1981 the Waste Management Branch directed Westmin to conduct a monitoring program of water quality in a phased approach. This program was conducted through 1983 under the guidance of the Buttle Lake Study Committee composed of regulatory agencies, researchers and consultants (BC Research, 1981, 1982a, 1982b, and 1983; Simco Groundwater Research, 1983; Knight and Piesold Ltd., 1982). The main focus of the monitoring effort was Myra Creek and its floodplain with lesser emphasis on specific drainages from the Lynx Pit, tailings, and waste rock. Only the information relevant to waste rock is summarized here.

During the time of this previous work, the waste rock pile now known as Dump #1 was already in place along the north valley wall, resting on the Myra Creek floodplain. However, the tailings area and inner drain depicted in Figure 2.1 were not present. Surface drainage from the Lynx Pit was directed into the area around the toe of the dump and the floodplain (now covered by tailings). Water-quality monitoring of this drainage (Station M6, Figure 2.1 and Figure 2.2) showed that aqueous pH varied from acidic to near neutral with acidic pH appearing during wet periods when flushing of acid-generating pit walls was reportedly highest.

Seeps or springs, at which groundwater appeared on the floodplain, were also monitored during the study. Most of these seeps were acidic with pH around 3-4 (e.g, M11 and M15, Figure 2.2 and 2.3). Station M11 to the northeast of the dump appeared to have been neutral during initial monitoring then subsequently became acidic (Figure 2.3), although this may have simply been part of the annual variation in pH as noted in the pit drainage. Based on this information, the researchers concluded that the surface water and groundwater near the waste rock dump was contaminated by acidity and metals, particularly zinc, copper, and cadmium, and that the degree of contamination varied significantly with climatic conditions. The contamination was attributed to the waste rock, but it seems that pit drainage and the adjacent Tailings Road which was later found to generate net acidity, contributed to the contamination.

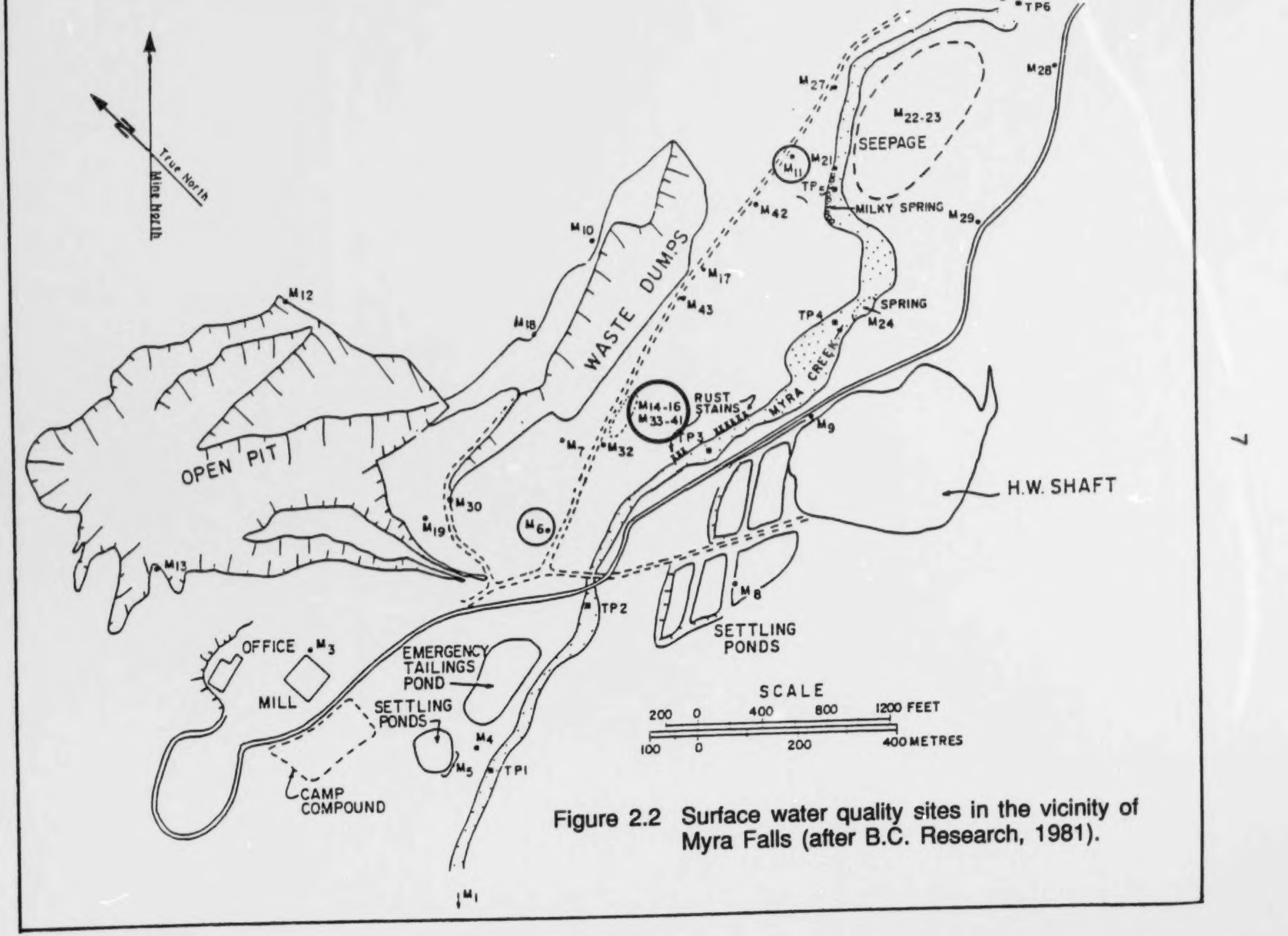

True North
Mine North
N
OPEN PIT
M12
M13
M18
M19
M30
M10
WASTE DUMPS
M17
M43
M42
M7
M32
M6
M14-16
M33-41
RUST STAINS
TP3
MYRA CREEK
M9
TP4
M24
SPRING
M11
M21
TP5
MILKY SPRING
M29
SEEPAGE
M22-23
M27
M2
TP6
M28
H.W. SHAFT
TP2
M8
SETTLING PONDS
OFFICE
M3
MILL
EMERGENCY TAILINGS POND
SETTLING PONDS
M4
M5
TP1
CAMP COMPOUND
M1
SCALE
200
0
400
800
1200 FEET
100
0
200
400 METRES

Figure 2.2 Surface water quality sites in the vicinity of Myra Falls (after B.C. Research, 1981).

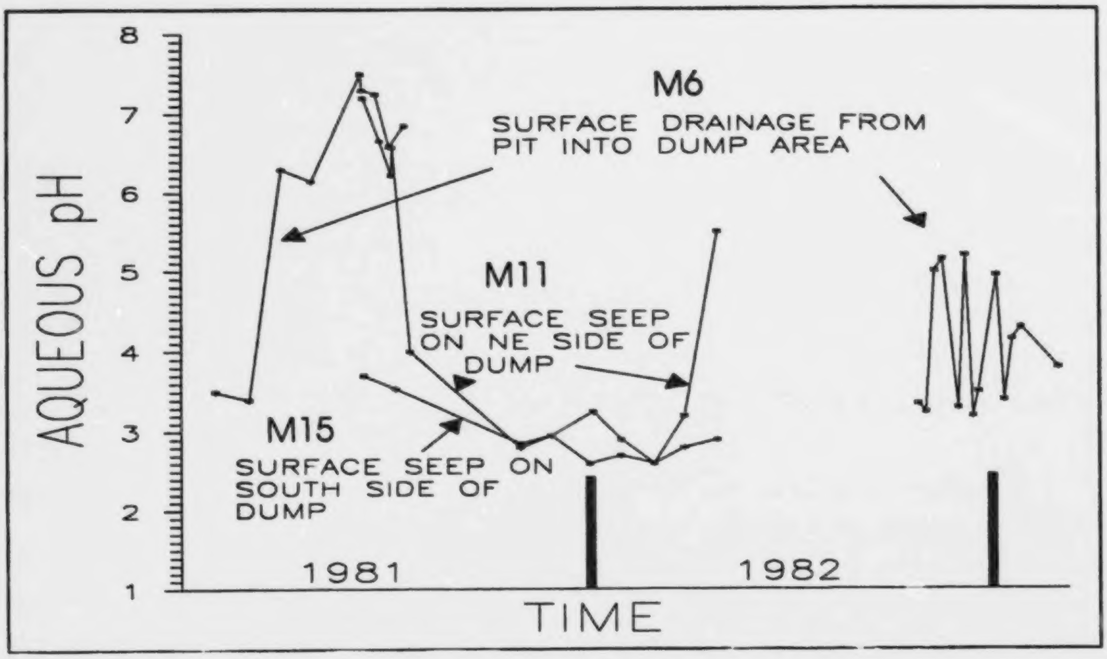


Figure 2.3 Aqueous pH vs time for pit drainage (Station M6) and surface seeps on the northeast side (M11) and southside (M15) of the waste rock dump.

Because of the recognition that the local groundwater system was contaminated with acidity and metals and that groundwater flow probably represented the major pathway of metal transport to Myra Creek, a detailed hydrogeologic study was conducted by drilling several boreholes and installing piezometers (Simco Groundwater Research, 1983). Additional piezometers were installed in pre-existing boreholes drilled into bedrock during exploration.

One borehole (S9, Figure 2.5, Section 2.3) was drilled through 38.4 meters of waste rock on the southwest side of the top of the dump and the drilling was halted when rock that was believed to be bedrock was encountered. Similar difficulties in distinguishing deeper waste rock from underlying bedrock were encountered in later drilling (Section 2.3), highlighting the physical and geochemical similarities of the two rock types. Except for water at depths of 4.3-4.6 meters, there was no reported water table located in the borehole. A shallow piezometer at 4.3 m depth and a deeper piezometer presumably at bedrock at 38.4 m remained dry throughout the study. The researchers concluded that rainfall on the top of the dump (known as the "timber yard") trickled downwards through the waste rock and into the underlying bedrock, then migrated laterally towards the toe of the dump and Myra Creek.

A borehole (S10, Figure 2.5, Section 2.3) was drilled on the toe of the dump through 7.3 meters of waste rock into the underlying gravel and silts. The water table was found to be near the contact of the waste rock and gravel, based on two piezometers installed at S10. The shallow piezometer just below the water table (Figure 2.4) showed that the pH remained consistently acidic, although data span only about 1/2 of a year. The deeper piezometer showed an acidic pH during winter with an increase to near-neutral pH towards summer. Water levels and zinc concentrations in these piezometers displayed a 15-day delayed response to rainfall events on the dump. This confirmed the hydraulic connection to the dump with the delay reflecting the finite values of hydraulic conductivity. The trend of consistently acidic pH in the shallow piezometer is consistent with those of several seeps on the floodplain and the trend of seasonal pH fluctuation in the deeper piezometer coincides with that of pit drainage and possibly a seep to the northeast of the dump.

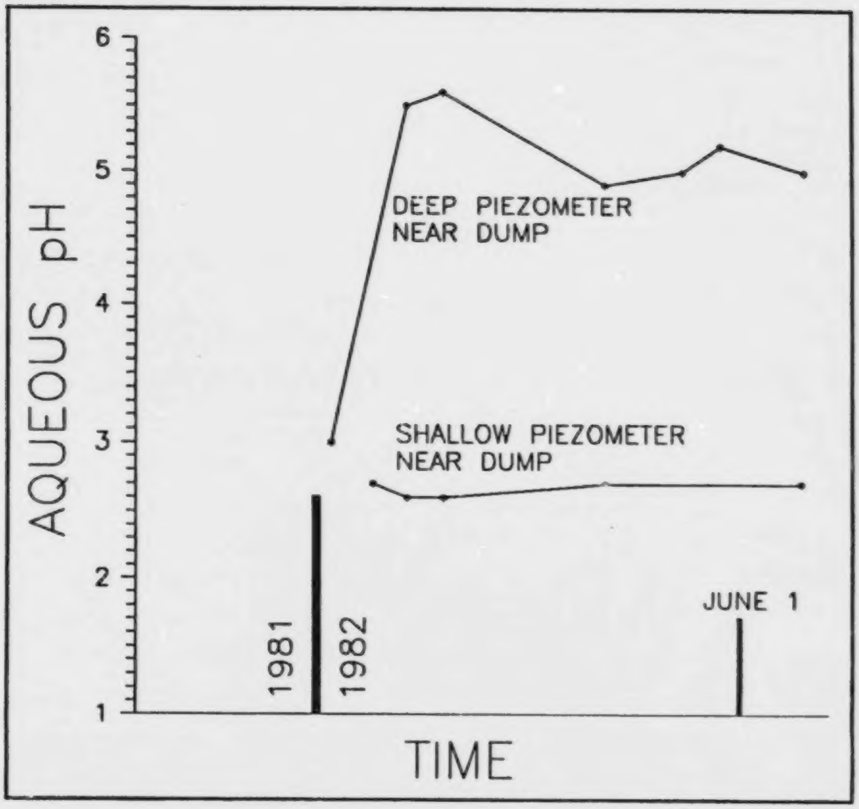


Figure 2.4 Aqueous pH vs time for piezometers drilled through the toe of the dump (S10) into underlying sediments.

Based on these findings, the researchers concluded that the area in and around the waste rock dump was contaminated by acidity and metals. Two more specific conclusions can also be drawn from re-interpretation of the information: (1) the historical exposure of the area to acid drainage has probably removed most or all of carbonate minerals in the area and (2) the subsurface strata have accumulated leachable metals. The first conclusion indicates that the natural environment is probably no longer capable of significantly neutralizing pH. Simplistically, this means that strata will not alter the chemistry of water passing through, although some buffering towards neutral or acidic pH may occur due to mineral precipitates from earlier contamination. Since the capacity for natural attenuation of aqueous contamination has apparently already been consumed near the waste rock, control of acid drainage at the source becomes the target of remediation. The second conclusion on metal accumulation carries major implications for remediation. Because subsurface strata have apparently accumulated leachable metals through adsorption and ion exchange, the strata will be capable of releasing relatively high levels of these metals for years or decades once remediation begins to supply uncontaminated water to the strata. As a result, the effects of remediation to control metal levels may not been seen for many years. Such a scenario has been found to apply to minesites such as the Rum Jungle in Australia where more than 15 years of clean flushing of the groundwater system is necessary before metal loadings to surface water are expected to decrease significantly.

For the Westmin site, a decrease in metal loadings to Myra Creek was an immediate goal, so in 1982 a groundwater collection system (the "outer drain") was installed parallel to the bank of the Creek. Water from this drain was directed to settling ponds located on the south side of Myra Creek for lime treatment. The system apparently succeeded in decreasing the metal loadings to the creek. However, the drain did not control contaminant sources (pit drainage and waste rock dump) or the subsurface flow through the floodplain. In fact, hydraulic gradients probably increased due to the drain, causing groundwater to move through subsurface strata at a faster rate and possibly accelerating metal accumulation. In any case, the interpretation of subsequent studies and the design of remediation plans are hampered by the complexity of this historical contamination. Following initial tailings deposition on the Myra Creek floodplain a second drainage system ("inner drain") was installed along the toe of the waste rock dump to further increase the capacity of the groundwater interceptor system as well as to develop sufficient beach area for the tailings impoundment.

2.3 Physical Hydrogeology

Recognizing the potential impacts of internal processes within the dump on acid-drainage control and reclamation planning, Northwest Geochem proposed an environmental assessment consisting of boreholes, monitor wells, acid-base accounting, water-quality analyses, and laboratory experiments. In order to define the physical hydrogeology of the area in and around the waste rock dump, the drilling/monitor-well program was conducted in 1988 consisting of 57 boreholes (Figure 2.5) with an average depth of approximately 29 meters (Knight and Piesold, 1989). The holes intended only for stratigraphic determinations were drilled with a tricone rotary bit and the holes for installation of monitor wells were drilled with an Odex hammer and casing. Up to 3 wells were placed in each of 22 selected boreholes for a total of 51 wells, using bentonite to isolate the monitored intervals in each borehole. Several of the well screens are located above the local water table to monitor significant increases in the elevation of the local water table and any perched water tables. During drilling, difficulties in distinguishing deep waste rock from bedrock were encountered so that (1) the physical and geochemical characteristics of the two rock types are similar and (2) some information such as depth to bedrock and thickness of waste rock may be inaccurate by as much as a few meters.

Interpretation of the borehole and groundwater data was aided by a conceptual model for water movement in and around the dump as depicted in Figure 2.6. The sources of water entering the dump are infiltration of precipitation and lateral flow from the adjacent valley wall, but the flow rates from these sources are not well defined at this time. The nature of water movement through the dump will vary with location and depth and will include (1) unsaturated flow through much of the shallower portions of the dump, (2) downward and lateral flow from the dump into underlying bedrock, and (3) upward and lateral flow from the bedrock into the dump. The exit pathways for water leaving the dump are beneath the toe of the dump as defined by previous studies (Section 2.2). However, due to the relatively recent presence of moist tailings and the inner drain (Figure 2.1), the current pattern of water movement in the vicinity of the toe remains undefined at this time.

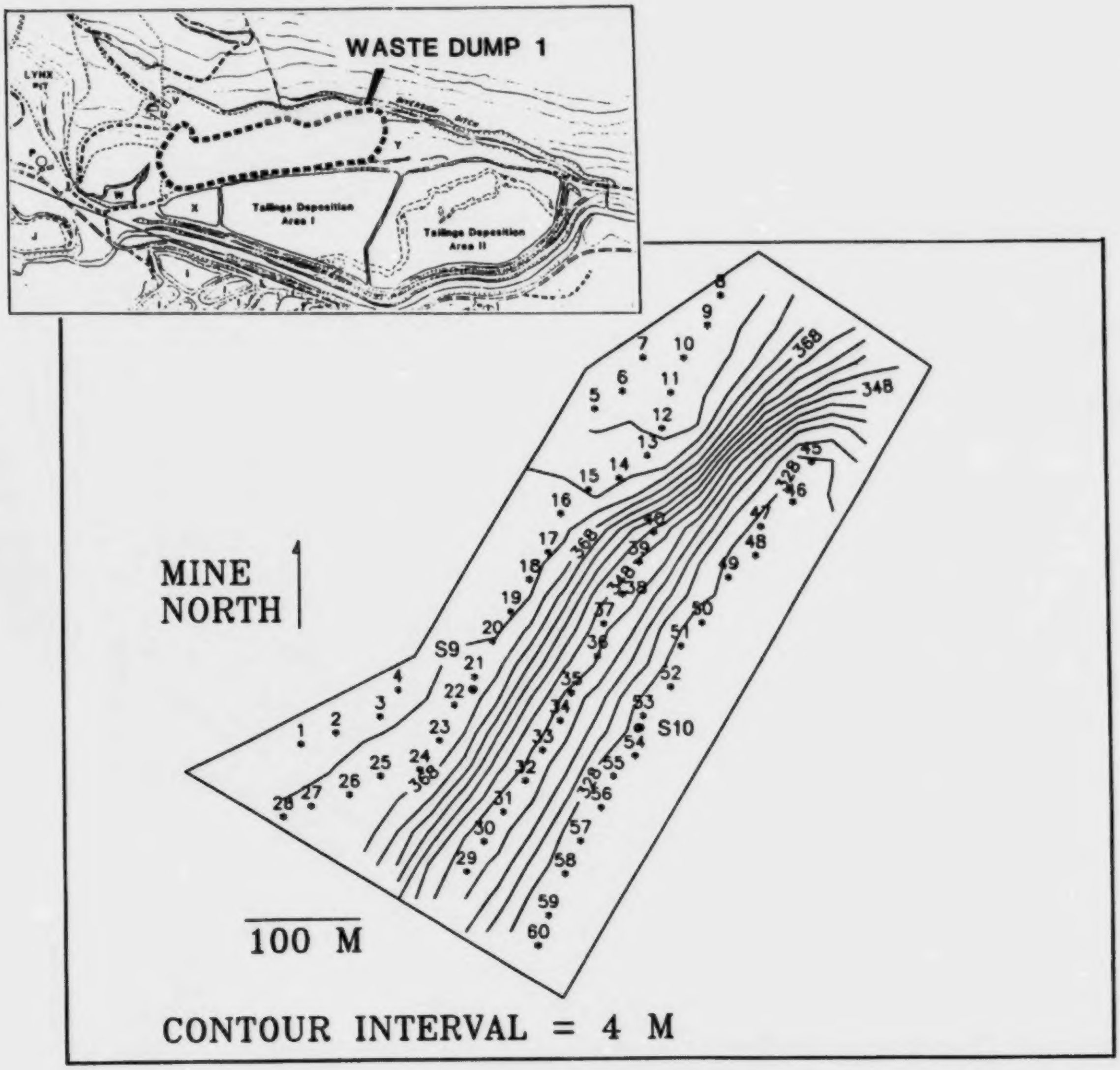

WASTE DUMP 1
LYNX PIT
DIVERSION DITCH
U
V
W
X
Y
J
I
Tailings Deposition Area I
Tailings Deposition Area II
MINE NORTH
100 M
CONTOUR INTERVAL = 4 M
368
348
328
348
368
328
S9
S10
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure 2.5 Borehole locations and surface elevations at the waste rock dump.

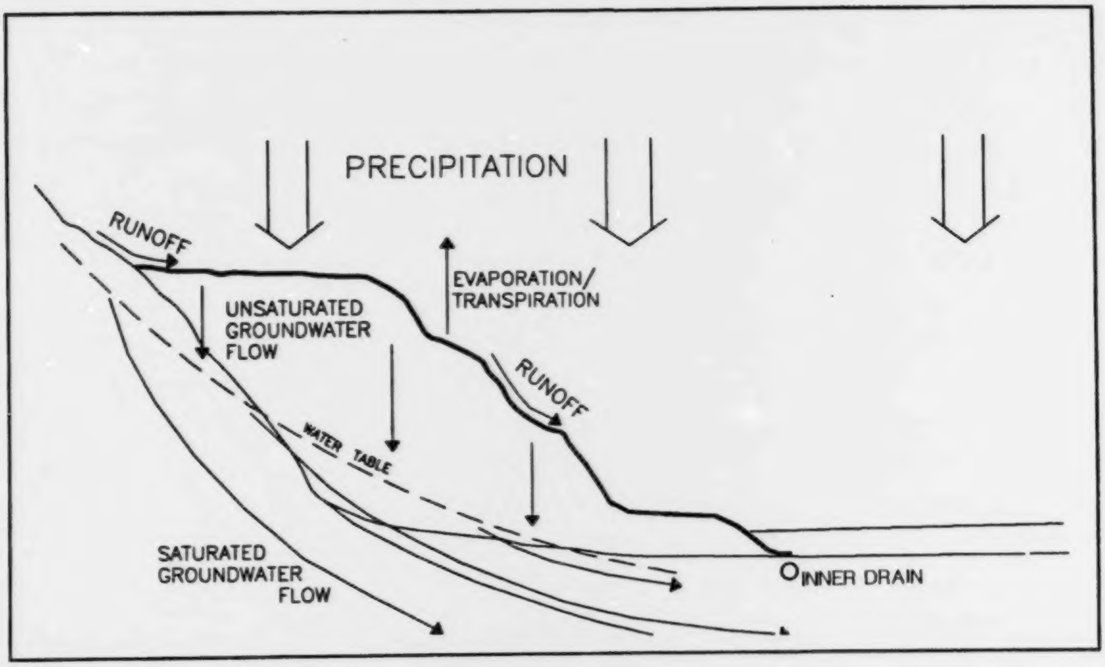

PRECIPITATION
RUNOFF
EVAPORATION/
TRANSPIRATION
UNSATURATED
GROUNDWATER
FLOW
RUNOFF
WATER TABLE
SATURATED
GROUNDWATER
FLOW
INNER DRAIN

Figure 2.6 Conceptual model of water movement in and around the waste rock dump.

2.3.1 Stratigraphy

Based on interpretation of borehole logs for each borehole, the original land surface beneath the waste rock (Figure 2.7) consisted of fractured bedrock with an overlying layer of peat-like organic material. The organic layer is generally 1 meter thick on the valley wall (Figure 2.8). Beneath the toe of the dump, the organic layer increases locally in thickness to approximately 10 meters. This increase is correlated with the presence of alluvium and/or highly fractured bedrock, indicating the organic layer formed in a stream channel and/or an eroded fault zone.

The organic layer is now highly disturbed and distorted due to the disposal of waste rock. In several locations, the rock has partially displaced the organics, causing the organic material to squeeze upwards by a few meters into the rock mass. In other locations, the organic layer was apparently excavated and placed onto lifts elsewhere in the dump (e.g., at Boreholes 4 and 16).

The dump contains sulfide-bearing rock from the underground and open-pit mining operations. The major ore minerals are chalcopyrite, sphalerite, galena and bauxite. Gangue minerals include quartz, sericite, chlorite and pyrite. Ore deposits occur as lenses of massive sulfide and associated disseminated sulfide. The ores vary in composition within as well as among lenses. This variability is consequently reflected in the mineralogy of the waste rock dump. The rock is well indurated, but not particularly hard, so that the waste rock near the base of the dump has likely been crushed to a grain size finer than as originally placed. This process explains the difficulty in distinguishing lower waste rock from bedrock during the 1981 and 1988 drilling programs and the apparently similar values of hydraulic conductivity for the lower waste rock and bedrock. The thickness of the waste rock reaches a maximum measured thickness of 42 meters at Borehole 23 (Figure 2.9).

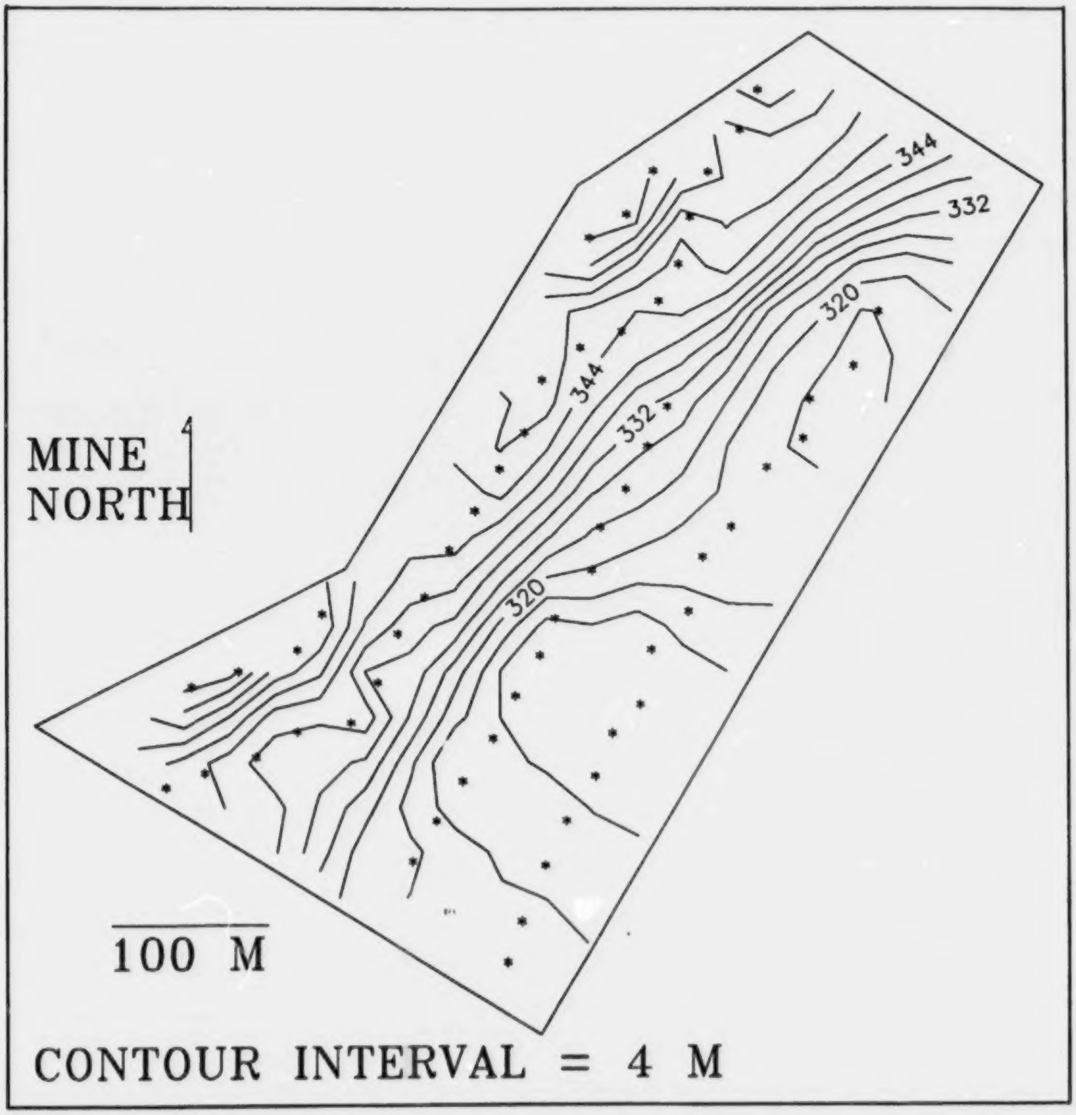

344
332
320
344
332
320
MINE NORTH
100 M
CONTOUR INTERVAL = 4 M

Figure 2.7 Elevation of original land surface at the waste rock dump.

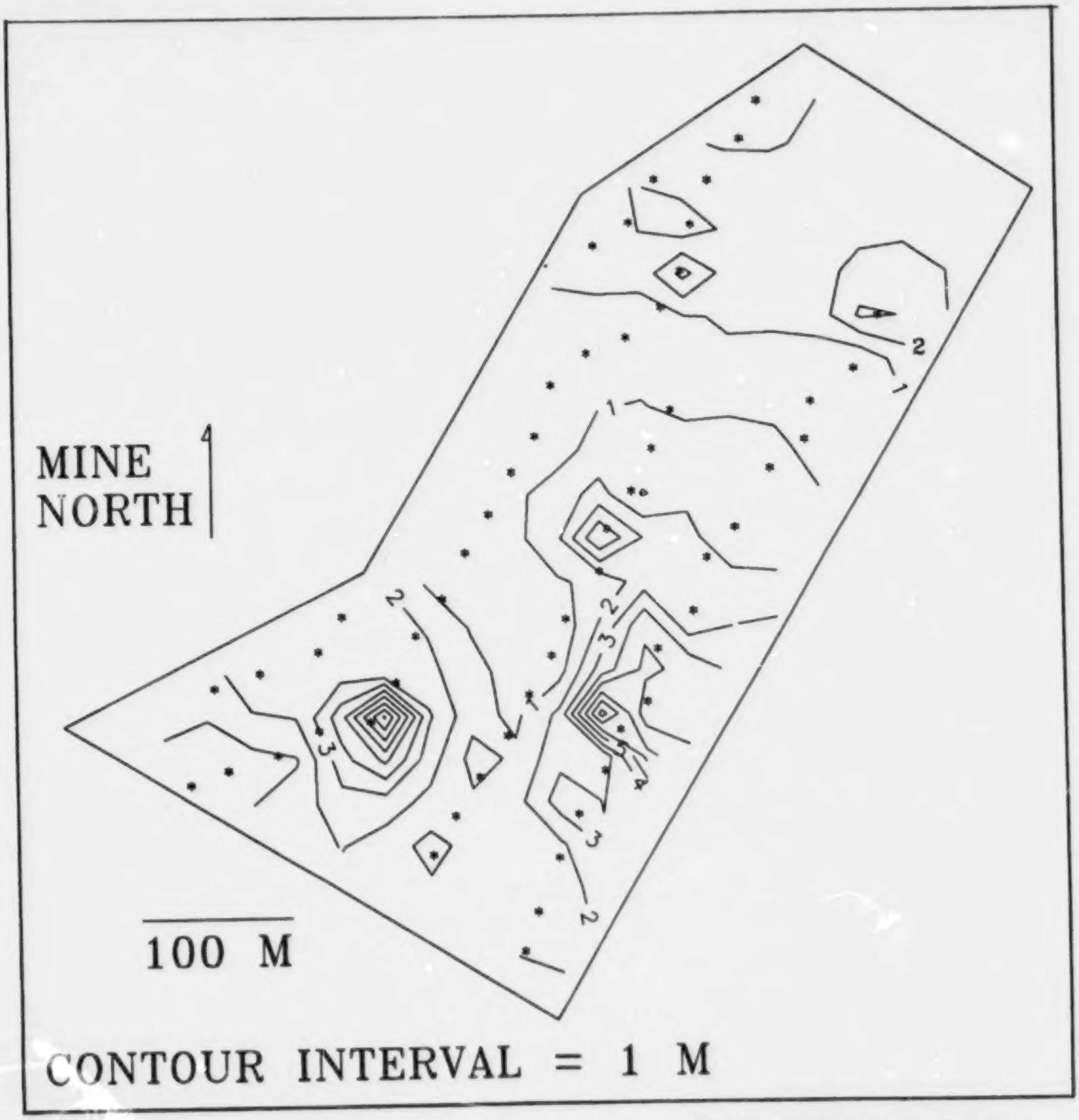

MINE NORTH
2
1
1
2
2
3
3
1
3
4
3
2
100 M
CONTOUR INTERVAL = 1 M

Figure 2.8 Thickness of the organic layer beneath the waste rock dump.

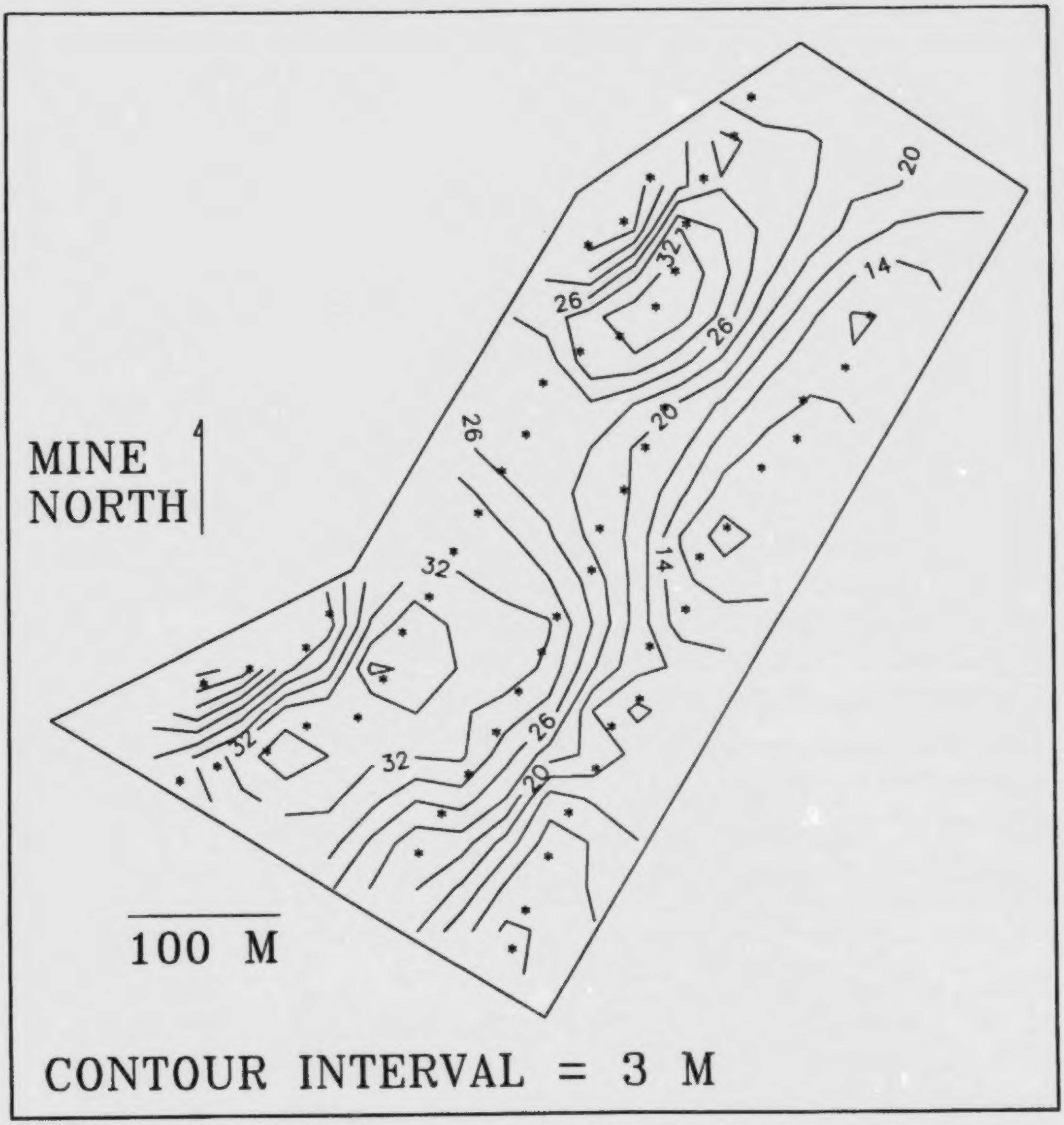

20
32
26
14
26
20
26
MINE
NORTH
14
32
26
32
32
20
100 M
CONTOUR INTERVAL = 3 M

Figure 2.9 Thickness of the waste rock within the dump.

2.3.2 Groundwater Movement

The groundwater moving through and beneath the dump has two primary sources. The first source is precipitation falling on the top of the dump, which then infiltrates downward into the dump. The second is groundwater discharging laterally through the north valley wall directly into the adjacent waste rock. This lateral drainage originates in infiltration from higher elevations and from leakage from the upper diversion channel. Data from the studies in the early 1980's (Section 2.2) and water levels measured during recent rainfall events indicated that the water table in and below the waste rock fluctuates by up to a few meters seasonally and during heavy rainfalls.

Within the dump, groundwater in the unsaturated zone (above the water table) likely flows generally downwards with the potential for some lateral movement. However, low-permeability layers within the dump lead to the development of perched water tables such as found at Boreholes 16, 22, and 55. These perched zones represent saturated regions where water is retained for relatively long times and is slowly released for downward flow to the local water table. The movement of water in the unsaturated part of any rock dump is difficult to monitor and has apparently never been characterized except through theoretical computer simulations (Northwest Geochem, 1990). Once water migrating through the unsaturated zone reaches the water table, it joins the groundwater moving through the saturated zone roughly parallel to the slope of the water table (Figure 2.6).

The slope of the water table in or below the Westmin dump can be determined from water levels measured in the monitor wells. However, the water levels must be carefully evaluated in light of factors such as well installation and development in a rock-pile environment. A critical evaluation of water-level and geochemical data from each well was performed to determine which wells were likely providing true water-table elevations. The locations of the selected wells and the interpolated elevations of the water table during September 1988 are presented in Figure 2.10.

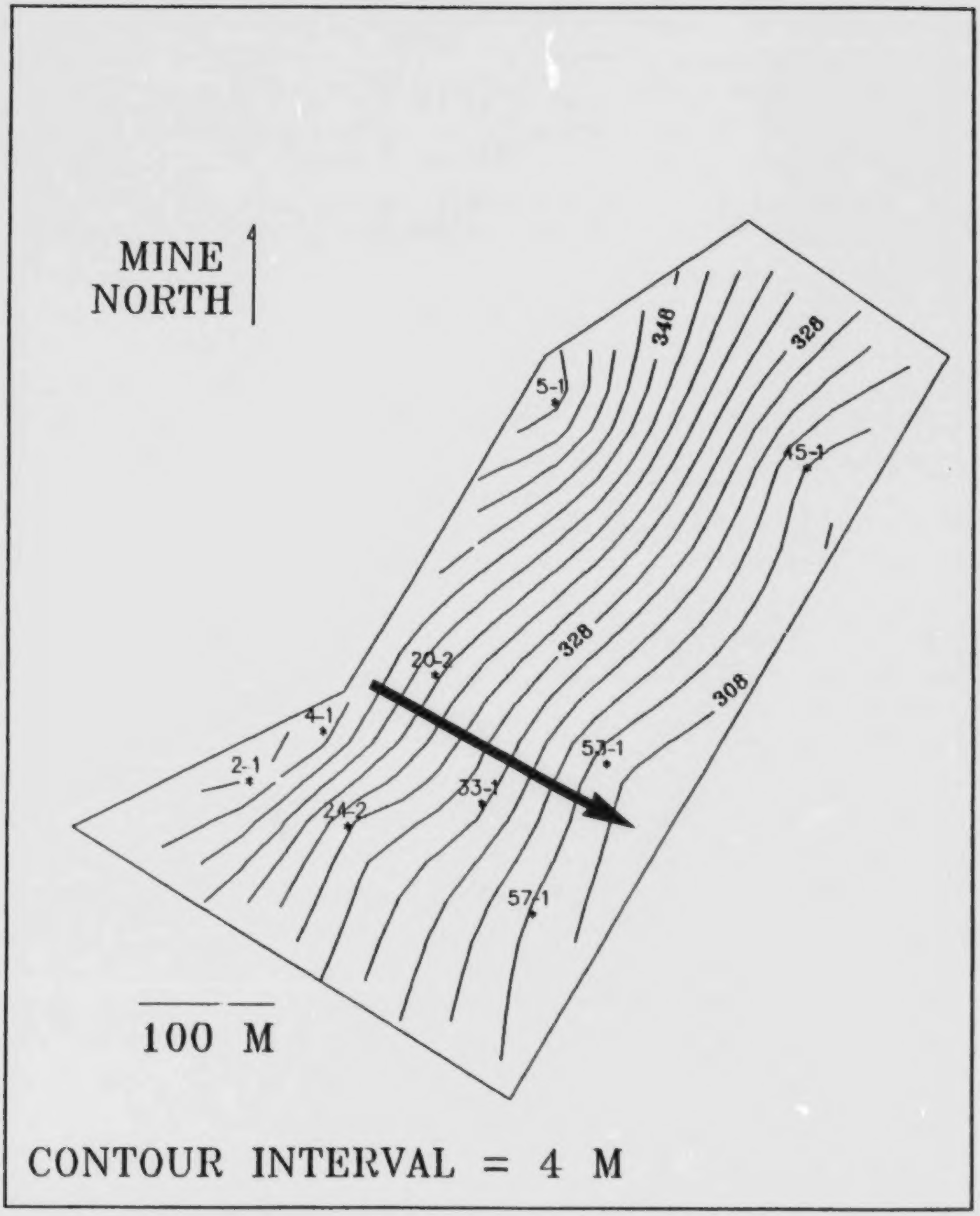

MINE
NORTH
348
328
5-1
45-1
328
20-2
308
4-1
53-1
2-1
33-1
24-2
57-1
100 M
CONTOUR INTERVAL = 4 M

Figure 2.10 Water table elevation in and beneath the dump. An approximate value (error less than 4m) has been inserted at 45-1 for orientation of contour lines.

The water table (Figure 2.10) has a relatively steep gradient of approximately 0.2 towards the valley floor to the south and east. There is a lack of accurate data in the eastern portion of the dump so an approximate value had to be inserted at Borehole 45-1 to prevent the contouring program from anomalously locating contours through the central portion of the dump. The value at Borehole 45-1 was based on a few measurements and probably has an accuracy better than 4 meters.

Despite variations in the water table of up to a few meters during seasonal changes in precipitation, there is little effect on the value of hydraulic gradient due to its relatively high value (the contour interval in Figure 2.10 exceeds the seasonal variation in water levels). This behavior suggests that infiltration is relatively uniform across the top of the dump or that infiltration is well distributed as it reaches the water table at depth.

In a hypothetical coarse-rock dump with an impermeable layer underlying the dump, groundwater would flow downwards to the base of the dump, then create a saturated zone with a water table above the base. This water would then flow downslope and exit at the toe of the dump. The Westmin waste-rock dump does not fit this hypothetical scenario because the underlying layer is not impermeable relative to the base of the dump. Firstly, previous studies (Section 2.2) concluded that the water table was beneath the dump within the bedrock. Secondly, the water table in 1988 and 1989 was found to be a few meters below the dump (within the bedrock) in places and a few meters above the base of the dump in other locations. Thirdly, there is little seasonal fluctuation in the hydraulic gradient despite significant seasonal variations in precipitation. The generally continuous slope of the water table as it passes through bedrock and waste rock in various locations suggests significant and continuous hydraulic interaction between the bedrock and waste rock and similar permeabilities, resulting in one integrated groundwater system. This is consistent with the difficulty in distinguishing deeper waste rock from bedrock during drilling.

Hydraulic conductivities of the bedrock based on 4 single-well tests ranged from 3.2 x 10^{-8} to 1.6 x 10^{-6} m/s (Knight and Piesold, 1989), which was consistent with earlier measurements in abandoned exploratory holes of 10^{-7} m/s for fractured bedrock (Simco Groundwater Research Ltd., 1983). The hydraulic conductivity of the waste rock appears to be greater than 10^{-4} m/s (Knight and Piesold), but this value likely applies only to the coarser rock. The finer rock, particularly crushed rock near the base of the dump, probably has a much lower conductivity. Because of the similar hydraulic behavior of deeper waste rock and bedrock, these rock types probably have similar values of conductivity on the order of 10^{-6} to 10^{-5} m/s.

With a water-table slope of 0.2 and hydraulic conductivities around 10^{-6} to 10^{-5} m/s, a 1-square-meter cross-section of saturated rock would pass about 17-170 liters/day or 6,300-63,000 liters/year. The corresponding linear velocities are dependent on porosity which has not been defined, but with an assumed porosity of 0.1 the linear velocity would be approximately 0.17-1.7 m/day. Again, these values are considered representative of the lower rock below the water table; the coarser, shallower waste rock would conduct water at a much higher rate to the water table, but this upper unsaturated rock has not been instrumented. Nevertheless, this scenario can account for the significant fluctuations in water levels in that water moves rapidly downward to the water table where the lower conductivity cannot transmit all of the water, causing the water table to rise.

At the calculated velocities, up to hundreds of days are required for groundwater to move from the north valley wall to the Myra Creek floodplain and the inner drain. Earlier studies (Section 2.2) have indicated that water levels and aqueous zinc concentrations in sediments beneath the toe respond within 15 days to rainfall events, which likely indicates that this initial response is from nearby areas of the dump rather than the more distant upgradient areas of the dump. This is also supported by the relatively constant water chemistry in the upgradient portions of the dump and the fluctuating water chemistry in the downgradient portions (Section 2.4).

2.4 Chemical Hydrogeology

Chemical hydrogeology refers to the solid, liquid, and gaseous geochemical reactions that account for groundwater chemistry and the manner in which groundwater movement affects the geochemical reactions. In an acid-generating waste-rock dump such as Westmin's dump at Myra Falls, the major concerns are acid generation, acid neutralization, migration of acidity, and metal leaching.

2.4.1 Acid Generation, Migration, and Neutralization

As part of the drilling program discussed in Section 2.3, rock and sediment samples were collected from boreholes beginning at a depth of 15 feet and were submitted for acid-base accounting (ABA). This procedure defines the overall potential of a sample to generate net acidity based on the balance between acid-generating and acid-consuming minerals. Specifically, ABA provides values of Maximum Potential Acidity (MPA) based on total sulfur, Neutralization Potential (NP), Net Neutralization Potential (NNP, or NP minus MPA), and paste pH. MPA indicates the total quantity of acidity that would be produced if all the sulfur, presumed to be pyrite, oxidized fully. NP indicates the capacity of the sample to neutralize acidic water. A negative value of NNP (NP minus MPA) indicates the sample theoretically has the potential to generate net acidity at some point in time, whereas a positive value theoretically indicates the sample will not generate net acidity unless the neutralization potential is preferentially removed. Paste pH reflects the occurrence of any retained acid generation in the sample prior to analysis.

Mean values of ABA parameters (Table 2.1) indicate that the waste rock has a significant capacity for generating acidity (MPA), which is not offset by the neutralization potential. As a result, the mean value for NNP is significantly negative and net acidity can be expected from the waste rock on average. ABA analyses of the organic material beneath the waste rock also had a negative mean value for NNP, suggesting that this material could also generate net acidity. However, the sulfur measured in the ABA analyses was probably organic sulfur, which may not be acid-generating or may be only slowly reactive as sometimes found in acidic peat bogs. ABA analyses of bedrock produced a positive value of NNP (Table 2.1), indicating that this rock will not generate net acidity on average. However, the range of ABA values for bedrock are sufficiently variable so that net acid generation may occur in some areas. Mean values for paste pH (Table 2.1) are above neutral indicating that on average the samples were not actively generating net acidity prior to analyses, although a large proportion of some samples was likely from inside boulders where active acid generation would not occur. However, the minimum value of 4.00 for paste pH in waste rock demonstrates the occurrence of active acid generation in some samples.

Table: 2.1
Summary of Acid-Base Accounting of Borehole Samples

	Mean	Minimum	Maximum
WASTE ROCK			
MPA[1]	111.7	0.6	437.5
NP[1]	23.6	1.7	50.4
NNP[1]	-88.1	-423.6	25.7
PASTE pH	7.22	4.00	8.16
ORGANICS			
MPA[1]	23.1	0.9	176.3
NP[1]	13.6	4.0	29.1
NNP[1]	-9.4	-159.3	25.0
PASTE pH	7.47	6.47	8.13
BEDROCK			
MPA[1]	7.3	0.3	122.5
NP[1]	12.9	5.1	67.4
NNP[1]	5.6	-89.7	66.5
PASTE pH	7.68	6.19	8.45

[1] as tonnes $CaCO_3$ equivalent/1000 tonnes of material

A more informative analysis of ABA results involves spatial trends along the lengths of individual boreholes, which highlights the locations of greatest potential for, or current generation of, net acidity. This analysis has identified four basic types of trends (Table 2.2): boreholes with no clear evidence of acid generation, boreholes with evidence of shallow (surficial) acid generation, boreholes with evidence of deeper acid generation, and boreholes that show that all of the waste rock is generating acidity. Although each type is found throughout the dump, many boreholes showing some acid generation are located along the northern perimeter (upper lift) of the dump (Figure 2.5), which is consistent with the findings of the previous groundwater study (Section 2.2) and with observations of enhanced snowmelt during winter in this area of the dump. Many of the boreholes on the middle and lower levels of the dump display no clear evidence of net acid generation through ABA analyses, although acidic groundwater is occasionally found in some of these boreholes.

Table: 2.2
Summary of ABA Trends In Boreholes

Boreholes Showing No Clear Trends (Mostly All Neutral)

1, 2, 12, 13, 16, 18, 23, 25, 27, 29,
30, 31, 32, 33, 34, 35, 36, 37, 38, 45,
46, 48, 49, 50, 52, 53, 54, 56, 57, 58,
59, 60

Boreholes Showing A Shallow Acid Zone (Depth to Acid Front in m.)

3 (14m), 4 (8), 6 (8), 9 (8), 10 (15),
11 (20), 19 (14), 20 (8), 24 (8), 26 (8),
28 (8), 40 (14), 41 (8)

Boreholes Showing Distinct Acid Zones at Depth (Depth in m.)

5 (9-13), 9 (20-26), 14 (20-26), 15 (8-14),
17 (14-26), 21 (23-26), 22 (9-13 & 27-31), 55 (9-20)

Boreholes Showing No Neutral Zone in Waste Rock (All Acidic)

7, 8, 47, 51

Borehole 26 (Figure 2.11) is an example of combined oxidation, acid generation, and consumption of neutralization potential primarily occurring at shallow depths of less than 10 meters. In fact, this trend is found in several boreholes (Table 2.2) so that in portions of the dump there appears to be a shallow acidic zone and a deeper neutral zone, separated by an "acid front". Where the thickness of the dump is minimal and acid generation is significant, the acid front has already passed through the full thickness of waste rock and reached the water table (Boreholes 7, 8, 47, and 51, Table 2.2).

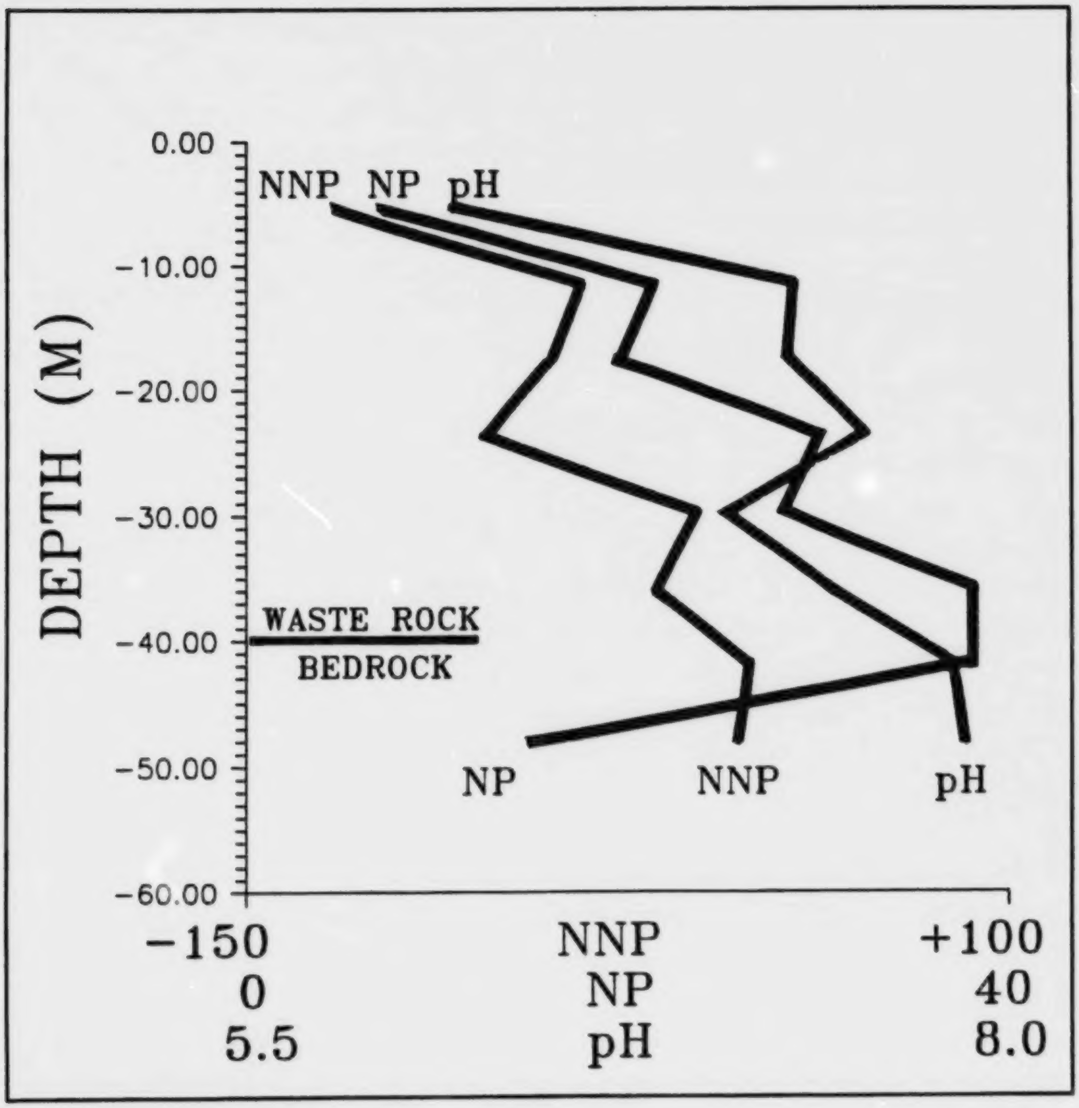


Figure 2.11 Results of acid-base accounting for Borehole 26.

Due to the complexity of water movement and the preferential movement through channels in waste rock dumps (Northwest Geochem, 1990), the acid front is not thought to be a flat, continuous surface, but simply a conceptualization to aid in understanding and discussing acid drainage in the dump. There is no other direct evidence for the shallow acid zone, such as water samples from the shallow unsaturated zone, nor are the measured paste pH values usually indicative of strongly acidic conditions (few values are below 5.0), but the seasonal appearance of acidic water below the water table (Section 2.5) during wet seasons suggests that the shallow acidic zone is occasionally flushed, at least in portions of the dump. The general lack of acidic values for paste pH may reflect the grinding of a sample to a paste, allowing neutralizing minerals within a rock to neutralize any acidity that may have been present on external surfaces.

In addition to the shallow acid zone, other geochemical features were detected within the dump. Zones of net acid generation at depth ("hot spots") occur within pH-neutral zones of boreholes (Figure 2.12 and Table 2.2). There are several potential causes for any particular hot spot such as anomalously more reactive sulfide minerals or little initial neutralization potential. Like the shallow acid zone, these zones supply acidity to water moving through them. Other features found within the dump include low-sulfur zones in which little acid generation can occur and anomalously high NP zones which can retard the migration of the acidity for long periods of time (Figure 2.13).

In general, most samples submitted for ABA analysis had negative values of NNP, indicating that overall the dump currently does not have sufficient capability to neutralize all of the acidity that can potentially be produced by the rock. Additionally, the measurement of acidic paste pH values in some samples with detectible NP and the occurrence of acidic groundwater in areas where ABA analyses identified detectible NP indicate a significant portion of NP is not available for neutralization (possibly located within rock rather than on exposed surfaces) or is not reactive. An analysis of ABA data and laboratory experiments (Section 2.4.2) concludes that NP contents of less than 20 tonnes $CaCO_3$ equivalent/1000 tonnes rock make no significant contribution to the neutralization of acidity.

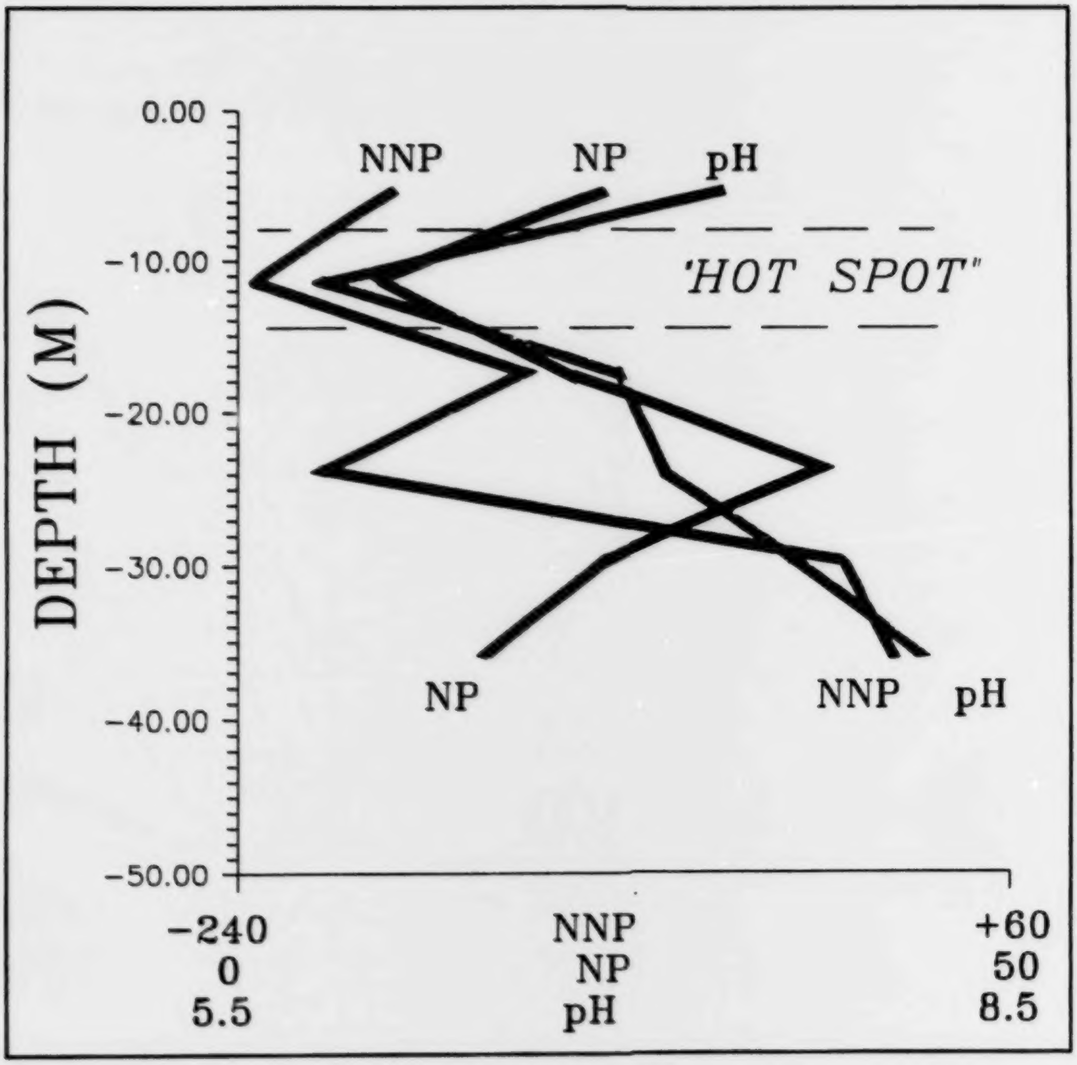


Figure 2.12 Results of acid-base accounting for Borehole 15.

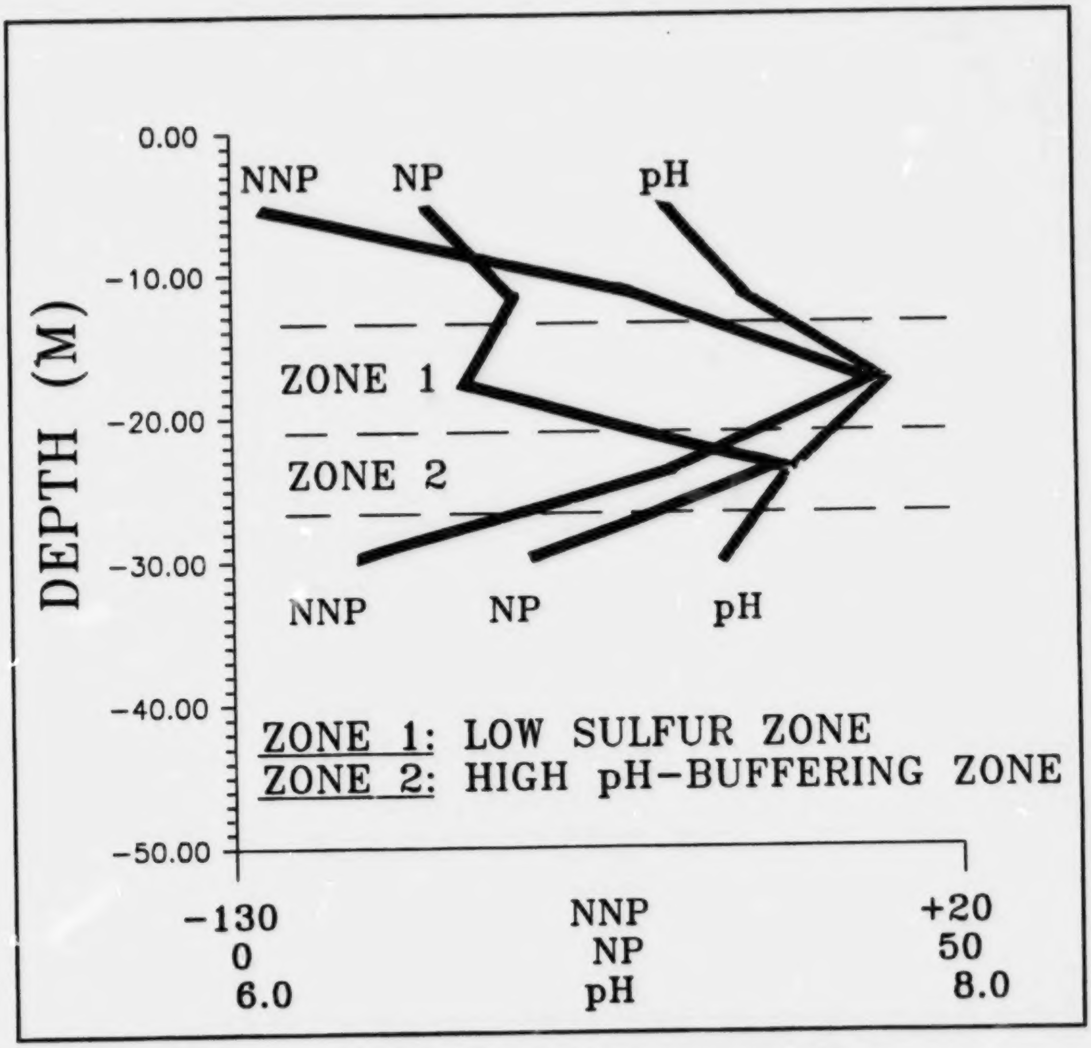


Figure 2.13 Results of acid-base accounting for Borehole 20.

2.4.2 Laboratory Tests of Acid Generation

In order to define rates of acid generation under laboratory conditions, leach columns and humidity cells were conducted. Six one-kilogram samples of oxidized waste rock were obtained from the same area of the waste rock dump to evaluate the degree of replication in studies of acid-generation characteristics. The samples were crushed to an average diameter of 1 cm and were placed in PVC columns of 7.8 cm diameter and 30 cm height. Deionized water was periodically poured into the columns and the standing water slowly drained through the column into a collection vessel. Chemical analyses of this effluent for acidity and pH were used to define rates of acid generation in the columns. Another sample of rock was crushed to less than 4 mm and placed in a humidity cell which maintained a dry-air environment for 3 days followed by 3 days of humid air. Deionized water was periodically poured into the cell and then drained from the cell after several minutes. Chemical analyses of this rinse water for acidity and pH were used to define rates of acid generation in the cell.

Acid-base accounting (ABA) of the bulk sample used for the columns indicated that the sulfur content was 3.93% S or 122.8 tonnes $CaCO_3$/1000 tonnes of rock. Neutralization potential was 11.5 tonnes $CaCO_3$/1000 tonnes of rock, which was shown to be not available for neutralization based on these tests and on borehole ABA studies (Section 2.4.1). ABA analysis of a subsample taken for humidity-cell testing indicated a sulfur content of 6.69% S or 209.1 tonnes $CaCO_3$ / 1000 tonnes of rock. As a result, the columns and humidity cell were expected to generate net acidity immediately and until all reactive sulfur was consumed.

Acidity concentrations in the column and humidity-cell effluents were converted to daily rates of acid production normalized to 1 kilogram of rock (Figures 2.14 and 2.15). Any neutralization of acidity in the columns and humidity cell would lead to an under-prediction of total acid generation, but effluent pH values of 3-4 suggest that neutralization was probably not overwhelming.

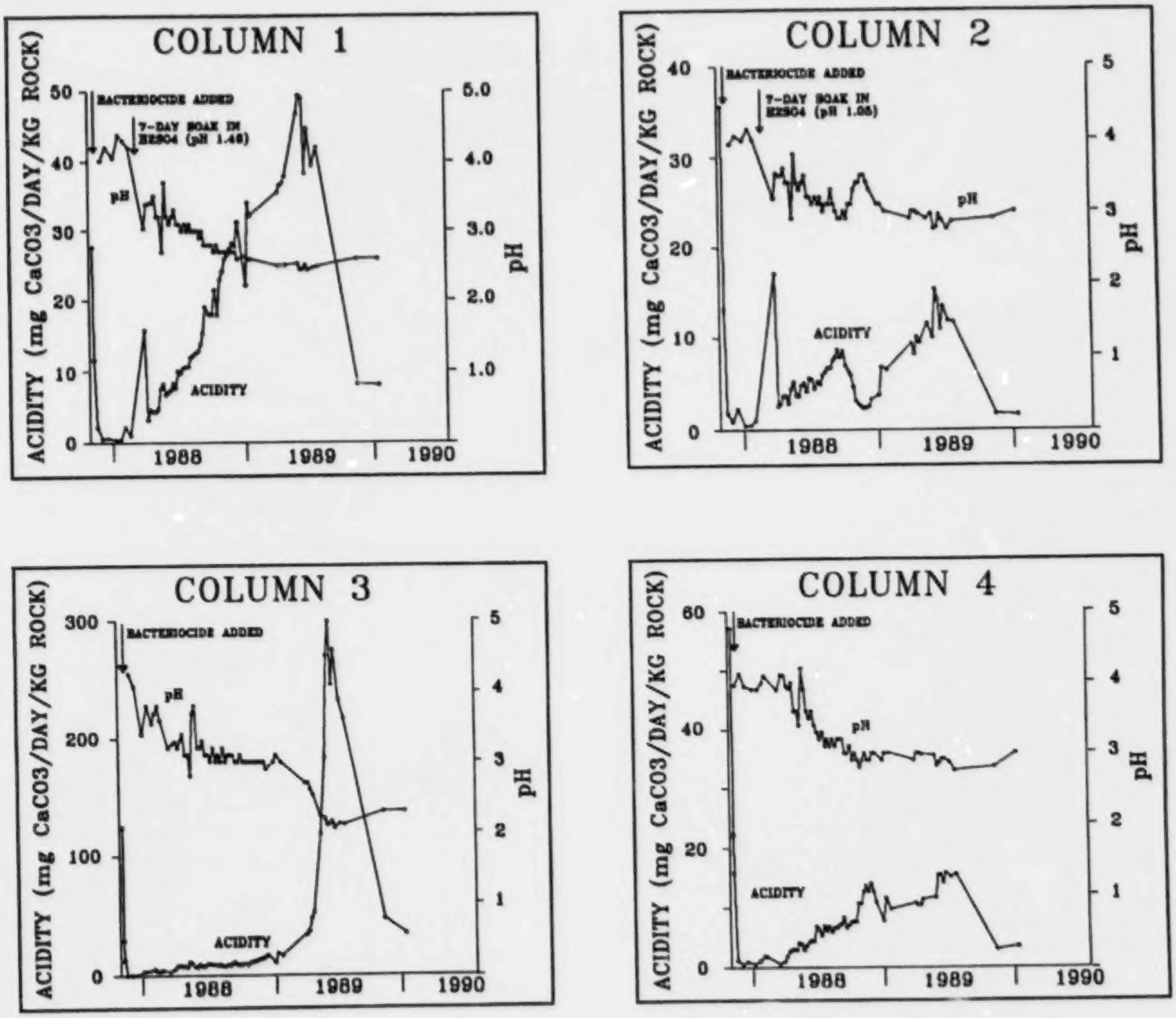


Figure 2.14 Effluent pH and rate of acidity production from Columns 1 through 4. Initial flushes of 941, 512, 1441 and 1207 mg $CaCO_3$/kg of rock, respectively, are not shown.

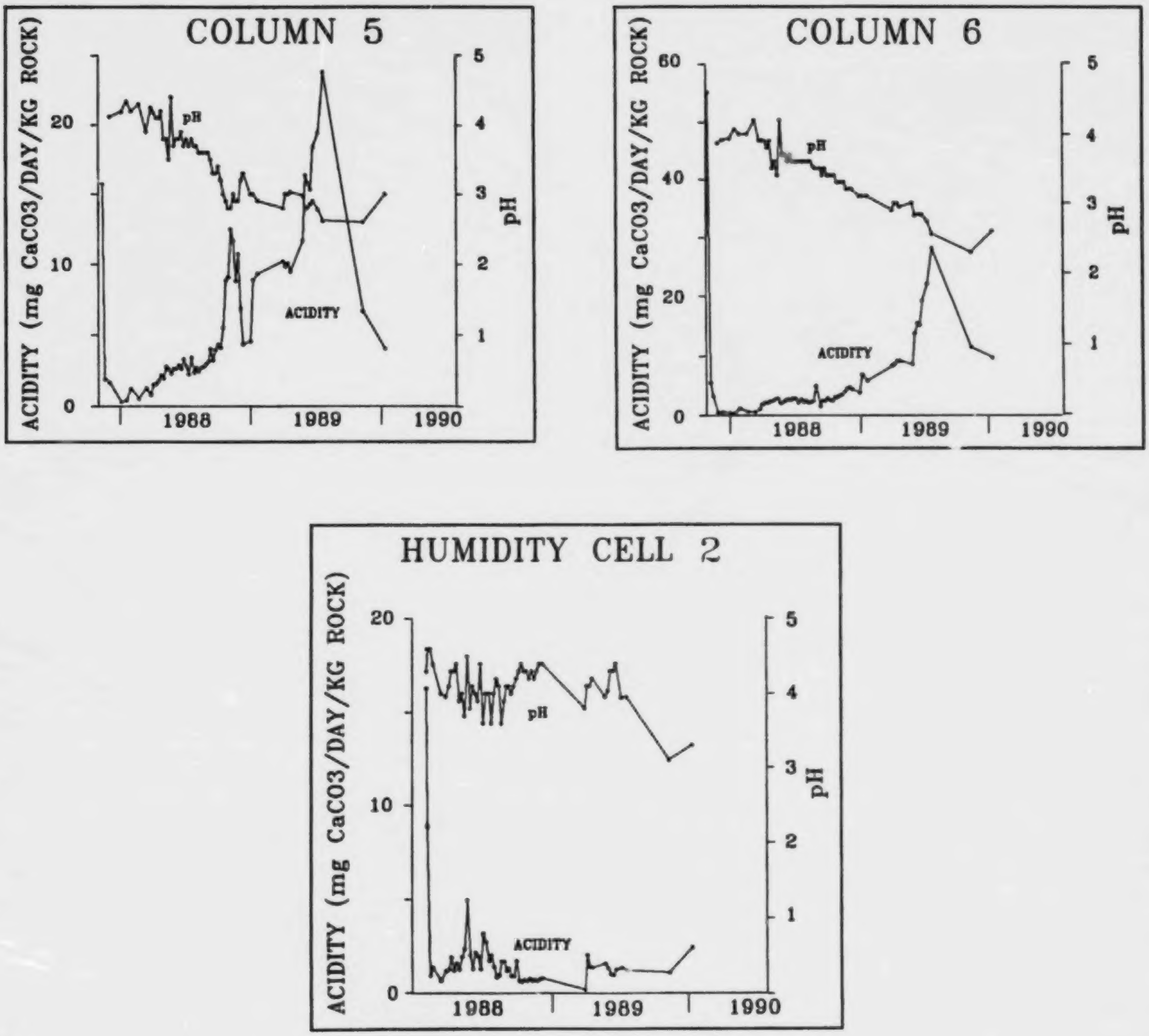


Figure 2.15 Effluent pH and rate of acidity production from Columns 5 and 6 and humidity cell 2. Waste rock used in humidity cell 2 is the same as that used in columns 1 through 6.

The early rates of acid generation showed that the rock initially contained acidity from previous acid generation and confirmed that the measured neutralization potential was not reactive. After the accumulated acidity was removed from the rock, rates of acid generation were low, generally less than 1 mg $CaCO_3$ equivalent/ day/kg, and pH values were around 4.0. Bactericide was added to Columns 1-4 during the initial flushing of accumulated acidity, but comparisons of these columns with Columns 5 and 6 indicated that the bactericide had no significant effect on acid generation relative to the variability among the columns. Additionally, diluted sulfuric acid (pH $<$ 1.5) was poured into and retained in Columns 1 and 2 for 7 days. After removal of the excess acidity, rates of acid generation were only slightly higher than before the acid soak, as was also noted in Columns 3-6. These results established that the acid soak, which would immobilize bacterial activity and remove any neutralization capacity, had no significant effect on acid production and that no significant neutralization was occurring within the columns.

Throughout 1988, rates of acid generation in the columns generally increased to 3-10 mg $CaCO_3$/day/kg with Column 1 generating almost 30 mg $CaCO_3$/day/kg. This was accompanied by a trend in decreasing pH. The increasing acidity and decreasing pH continued through most of 1989, although Column 3, which had weathered to finer-grained rock than other columns, produced over an order-of-magnitude increase in acidity. The trend of increasing acid generation through time may indicate processes such as (1) in-situ weathering of the rock so that progressively larger surface areas and more sulfide minerals are exposed to oxidation and (2) the periodic water flushes are not sufficient to remove all acidity so that acidity is continually accumulating within the columns. Tests will be carried out in 1990 to determine the causes of the increasing rates.

After August 1989, the columns were flushed only in November and in January of 1990, and the effluents contained the highest acidity concentrations (up 19000 mg/L) measured since the initial flush of acidity. However, the daily rates based on these two samplings were significantly lower than previous 1989 rates due to the length of elapsed time between samplings. A reasonable explanation for the lower daily rates may be the limitation of mineral solubility which would limit effluent concentrations and retain the remaining acidity within the columns. For this reason, retention of acidity is suspected and tests will be undertaken in 1990 to determine its extent. Nevertheless, most rates from Columns 1-6 indicate that acid generation is occurring at 1-30 mg $CaCO_3$/day/kg. If all sulfur in the rock is capable of generating acid, the columns could be expected to produce acidity for 9-300 years.

The humidity cell corresponding to Columns 1-6 (Figures 2.14 and 2.15) displayed an erratic, but more consistent, rate of acid generation and trend in pH than the columns. This may reflect the more complete flushing technique used in humidity cells, so that potential for accumulation of acidity is minor. In this case, the average rate of 2-4 mg $CaCO_3$/day/kg, which is consistent with other humidity-cell tests on rock from the dump (not shown), may also apply to the columns and lies in the lowest portion of the range noted in the columns. At this rate, hundreds of years would be required to deplete all of the sulfide minerals in the rock, assuming that all sulfide minerals are reactive and present rates of generation are maintained.

A leach column and humidity cell were also initiated for rock from Westmin's former Tailings Road, which has been identified as a significant source of acid drainage at the minesite. The results of the column (Figure 2.16) indicated a more typical trend in acid generation than Columns 1-6 with the rate of acid generation decreasing sharply then gradually decreasing through time. The long elapsed time between the final three measurements may have precluded the complete removal of acidity from the column, as was also suspected for Columns 1-6, accounting for the unrealistically lower rates.

The average rate of acid generation from the column was around 30-40 mg $CaCO_3$/day/kg based on data from late 1988 and 1989. This rate is significantly higher than the rates noted in Columns 1-6 and is supported by the lower pH values in this column compared to the others. The corresponding humidity cell (Figure 2.16) showed an unexplained high peak in 1989, but otherwise produced rates around 20 mg $CaCO_3$/day/kg, in general agreement with the column.

2.5 Impact of Acid Generation on Water Quality

If acid generation were to occur with no water flowing through the dump, then there would be no impact on water quality and no migration of acidity and leached metals. However, there is infiltration through the exposed surfaces of the dump and there is saturated groundwater flow near the waste-rock/bedrock contact. This water movement results in the migration of acidity away from the sites of generation, resulting in the degradation of water quality when in-situ neutralization is overwhelmed.

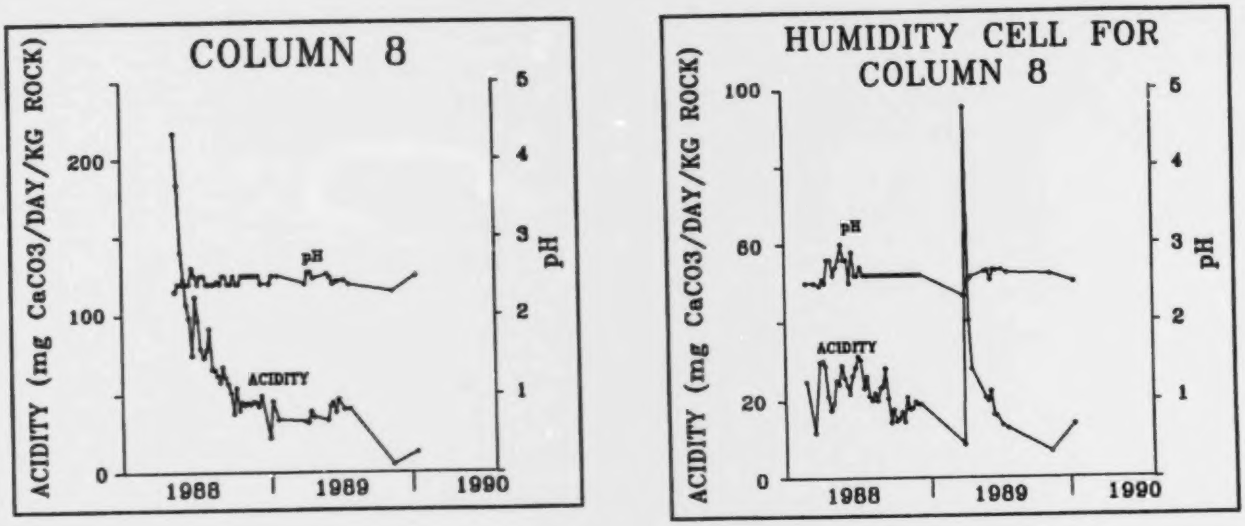


Figure 2.16 Effluent pH and rate of acidity production from Column 8 and the corresponding humidity cell.

Based on the results of Sections 4.1 and 4.2, the waste rock and bedrock do not have significant reactive neutralization potentials. Consequently, the main source of neutralization within the dump may be alkalinity in groundwater discharging laterally from the adjacent valley wall.

Measured values of pH for groundwater beneath the water table vary from about 2 to less than 9 (e.g., Figure 2.17). The sulfate concentrations (Figure 2.17) originate from sulfide oxidation and are therefore indicative of generation of acidity. However, waters with concentrations of sulfate below 100 mg/L have near-neutral pH, indicating neutralization is sufficient to overcome low levels of acidity. At greater sulfate concentrations, the capacity for neutralization is overwhelmed and pH is acidic. The scatter in the data of Figure 2.17 demonstrates the existence of variable capacities for neutralization by rock and water throughout the dump.

Metals such as zinc are leached from the waste rock as acid drainage moves through the dump (Figure 2.18). At acidic pH, a dependency of zinc concentration on pH in groundwater is apparent, but this relationship is not seen around pH 7-8 with zinc concentrations less than 10,000 ug/L. This suggests that either there is another geochemical control (such as dissolved inorganic carbon) regulating zinc concentrations at neutral pH or that waters with near-neutral pH are in contact with rock of varying zinc content. The highly variable concentrations of zinc at neutral pH are important for reclamation planning, which must address metal leaching as well as acid generation.

The groundwater has also been found to contain anomalous levels of other metals such as cadmium and copper around neutral pH. These concentrations appear to be independent of pH. Additionally, mercury has a larger percentage of significantly elevated concentrations at neutral and alkaline pH than at acidic pH, suggesting that the formation of aqueous mercury hydroxide complexes hence mobilizing mercury from the rock.

A comparison of sulfate and zinc concentrations (Figure 2.19) shows a positive correlation; however, this correlation may indicate either the zinc originates with the sulfate at sites of acid generation or the sulfate generally enhances zinc leaching from rock through aqueous complexation. The origin of variable zinc content at neutral or alkaline pH remains unresolved and possibly several geochemical factors are important

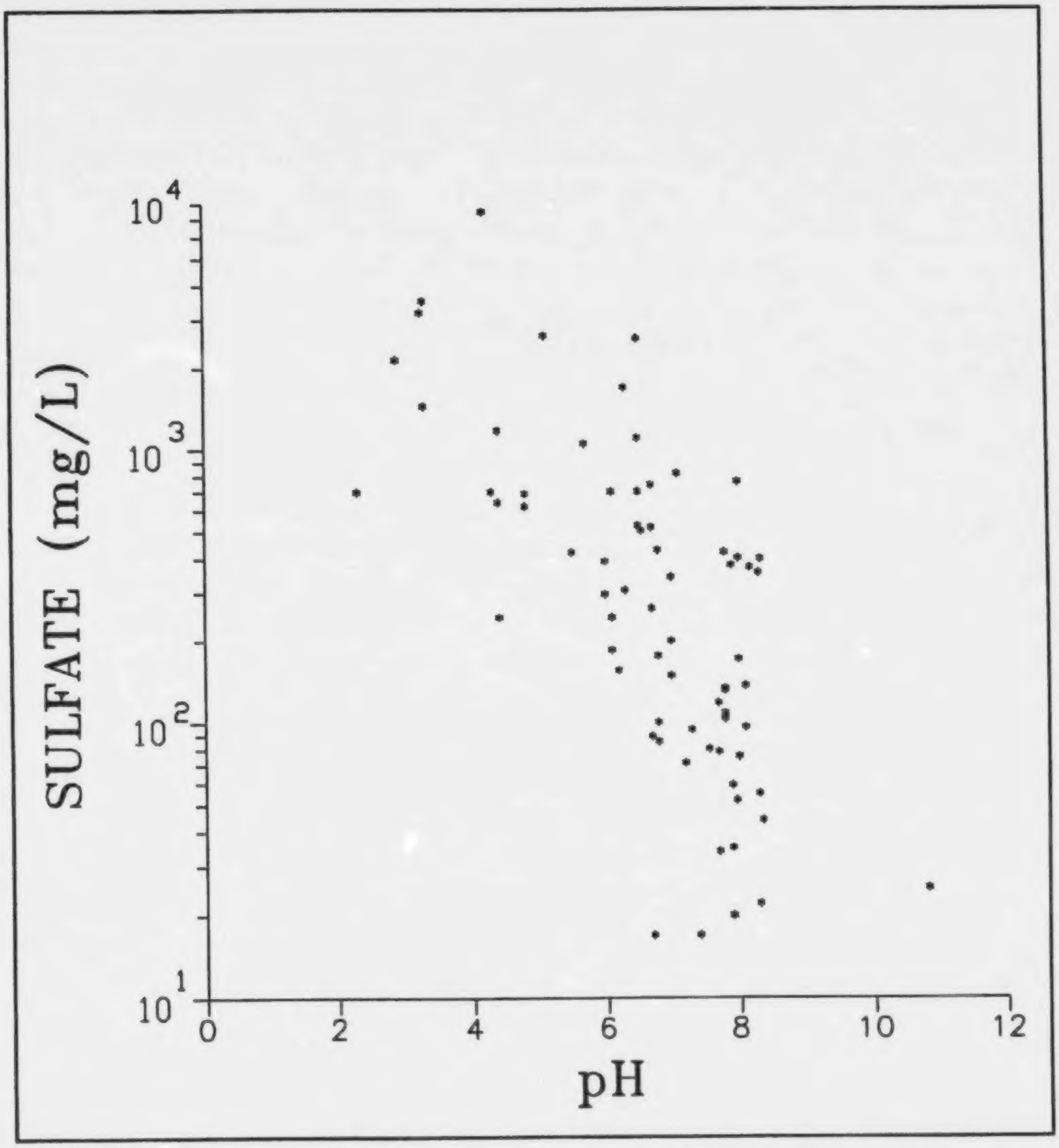


Figure 2.17 Sulfate vs pH for groundwater samples (1988, 1989 data).

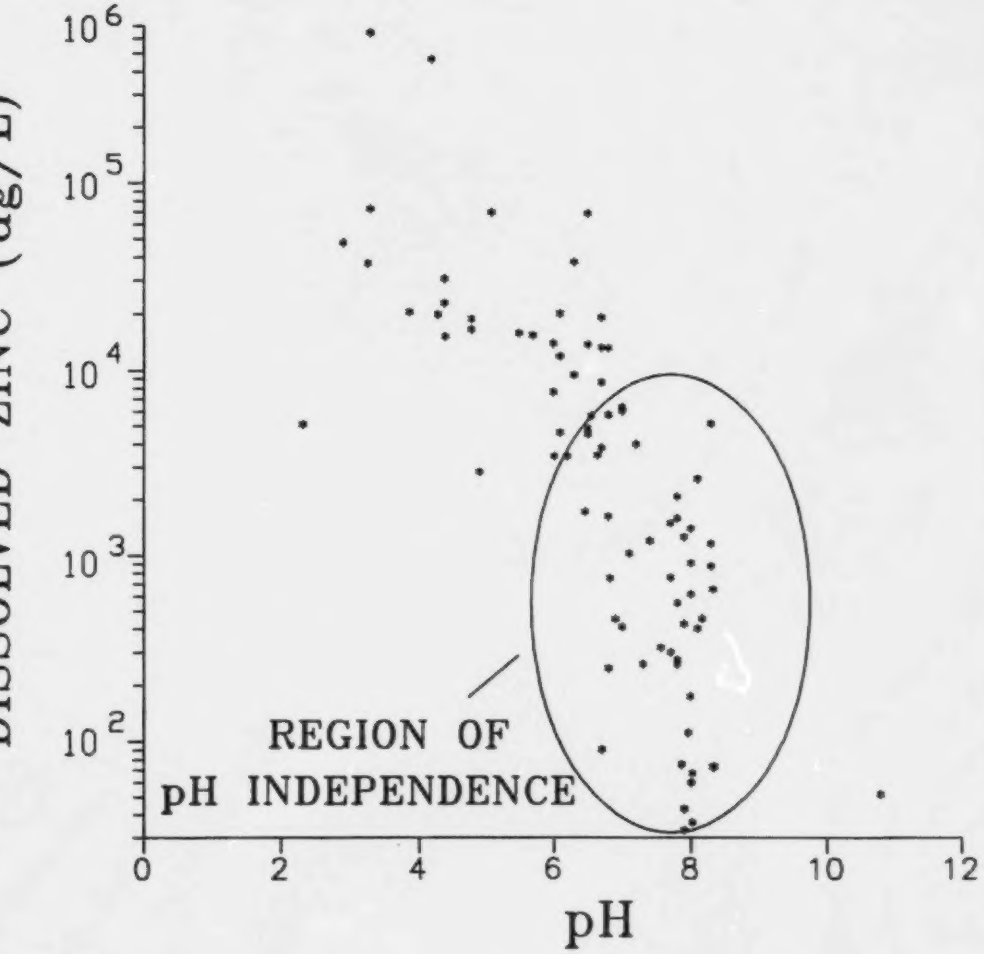


Figure 2.18 Zinc vs pH for groundwater samples (1988, 1989 data).

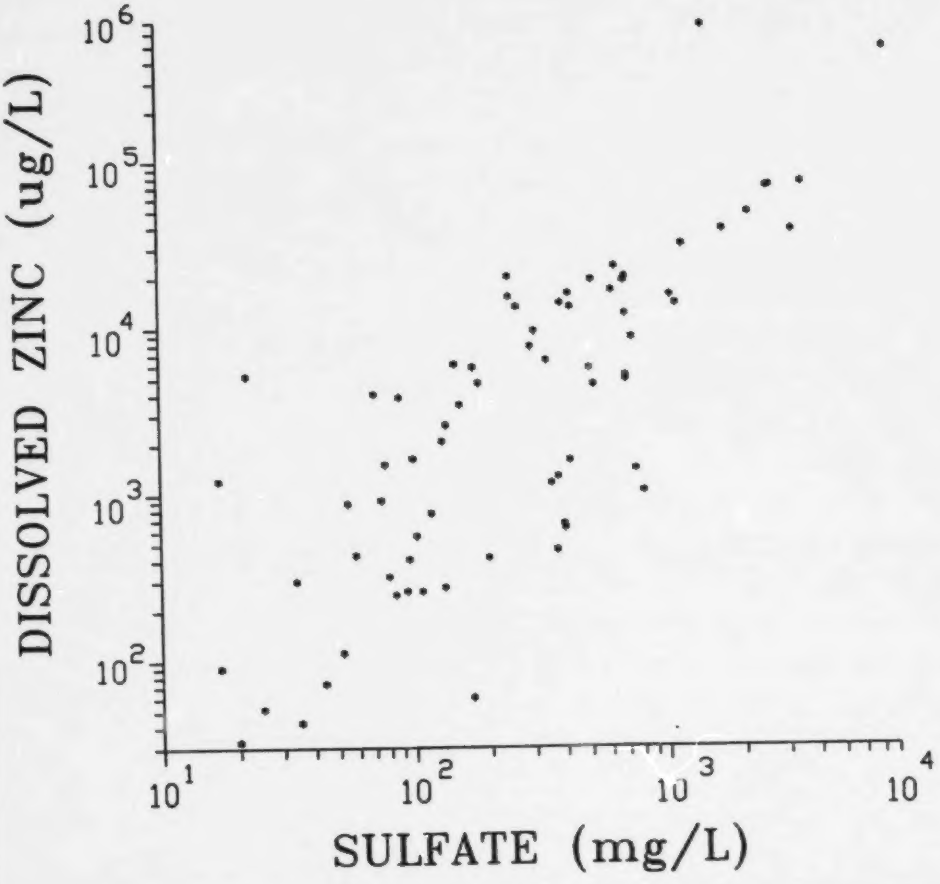


Figure 2.19 Zinc vs sulfate for groundwater samples (1988, 1989 data).

within the dump. Comparisons with other aqueous species have indicated similar dependencies of cadmium on sulfate concentrations and of copper on aluminum concentrations. Because of the high metal levels even at neutral pH, metal leaching as well as acid generation are objectives of the reclamation planning. Consequently, further geochemical interpretations are planned so that the causes and potential controls of metal leaching can be delineated.

Based on the physical hydrogeology of the area (Section 2.3), a portion of the saturated flow of groundwater apparently originates near the contact of the dump and the valley wall to the north. This groundwater likely remains chemically reducing because of the lack of contact with the atmosphere and, as a result, this water carries essentially no oxygen to promote acid generation as it moves through waste rock and bedrock. This is fortuitous because the waste rock and bedrock have little capacity to neutralize acidity based on acid-base accounting and laboratory experiments.

On the other hand, acidity is being generated in the acid zones of the dump and is occasionally migrating in the infiltrating water downwards to the water table where it encounters the deeper neutral water. The resulting water masses will then be either pH-neutral if there is sufficient alkalinity or otherwise acidic. As discussed earlier, sulfate (acidity) greater than 100 mg/L will often produce an acidic pH, indicating the background groundwater likely has a maximum alkalinity on the order of 100-200 mg/L. This is confirmed by measured alkalinities within the dump (Figure 2.20).

Spatial trends in groundwater chemistry along groundwater flowpaths beneath the water table are useful for detecting the progressive geochemical effect of the dump on water quality. For this examination, two flowpaths were identified based on availability of data. The western flowpath through the dump consists of nests 2, 24, 31/33, and 57 (Figure 2.5) and the only definable eastern flowpath passes through nests 5 and 45, although 45 is often dry. Only the western flowpath will be examined in detail here.

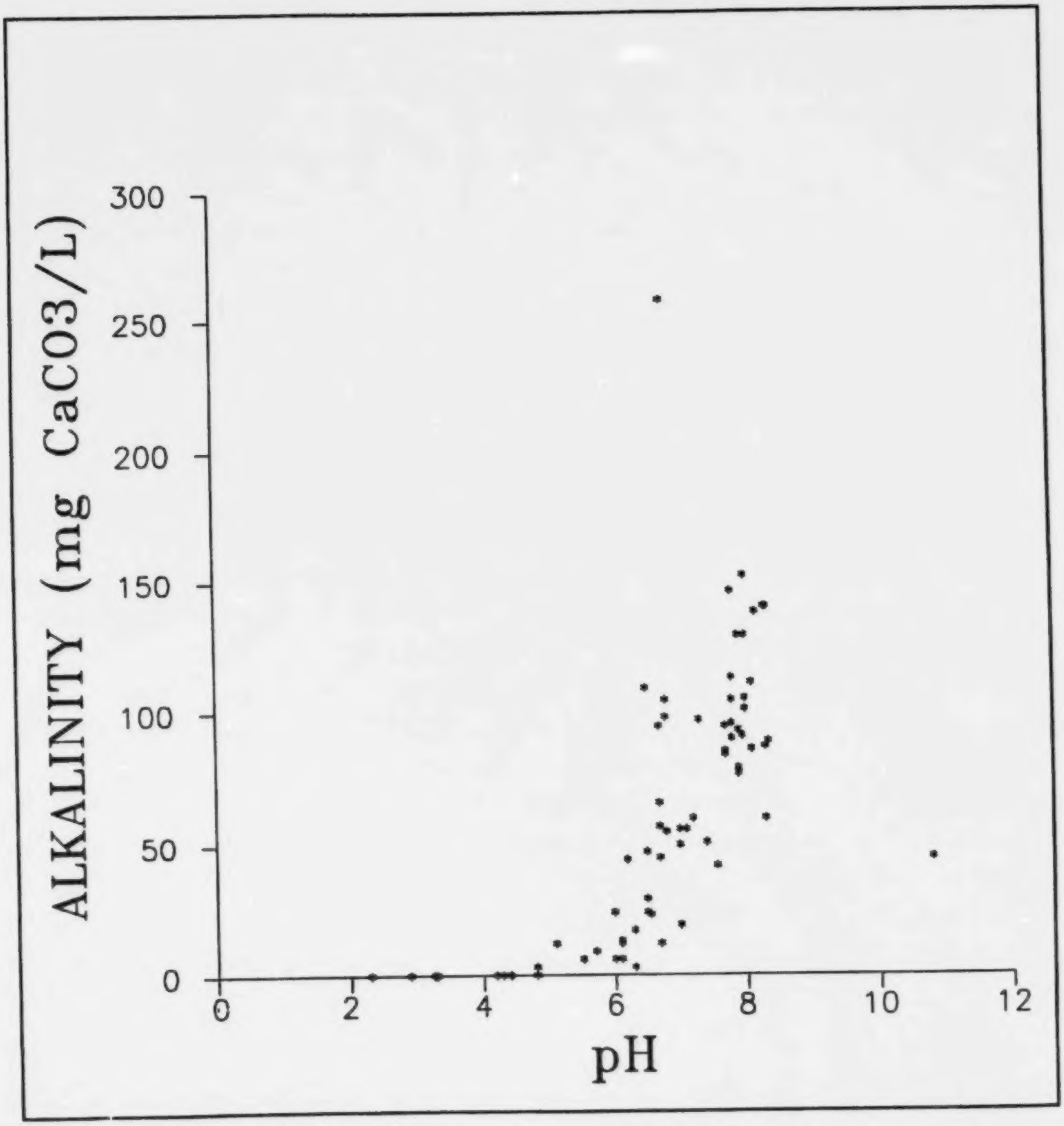


Figure 2.20 Alkalinity vs pH in groundwater (1988, 1989 data).

Seasonal trends in pH show that acidic pH water often appears in the western portion of the dump during the wet winter months when the acid-generating zones are flushed (Figure 2.21, also see Figure 2.3). During the summer months, these zones are not as frequently and extensively flushed so that the groundwater is more typically neutral. Nevertheless, a thin acidic layer of water just beneath the water table has been observed occasionally in the dump during drier months, probably reflecting a small amount of recharge to the saturated zone from the overlying acid zones.

When the acid zones are being actively flushed, a progressive degradation in water quality can be seen along the western portion of the dump (Figure 2.22). This degradation represents the input of highly acidic, metal-bearing water to the water table, which lowered pH to almost 3 and increased zinc concentrations by orders of magnitude in November, 1989. Sulfate concentrations, which are indicative of acid generation, increased significantly only in the lower portion of the dump suggesting that the toe of the dump produces most of the acidity. This is consistent with findings of previous studies (Section 2.2) and with calculated velocities (Section 2.3).

Based on laboratory tests, the rate of acid generation in the waste rock appears to be approximately 3 mg $CaCO_3$/day/kg. If the shallow acid zone in the dump (lateral extent of 800 m by 300 m) is about 10 meters thick, then the annual production of acidity in the dump is approximately 4.8×10^{12} mg $CaCO_3$. As discussed above, this acidity is primarily flushed during wet months. Quantities of water flowing through the dump are not known with sufficient accuracy at this time, but may be on the order of thousands of cubic meters each day based on assumed hydraulic conductivities and flow system dimensions. With a flow of 1000 m^3/day and an acidity concentration of around 1000 mg/L (from wet-season data), the daily removal of acidity is about 1×10^9 mg $CaCO_3$/day. Because this daily removal rate is less than 0.1% of the annual production, it appears that much of the acidity is retained within the dump. This retained acidity probably remains available for flushing so that remediation plans must address the control and retention/neutralization of the acidity.

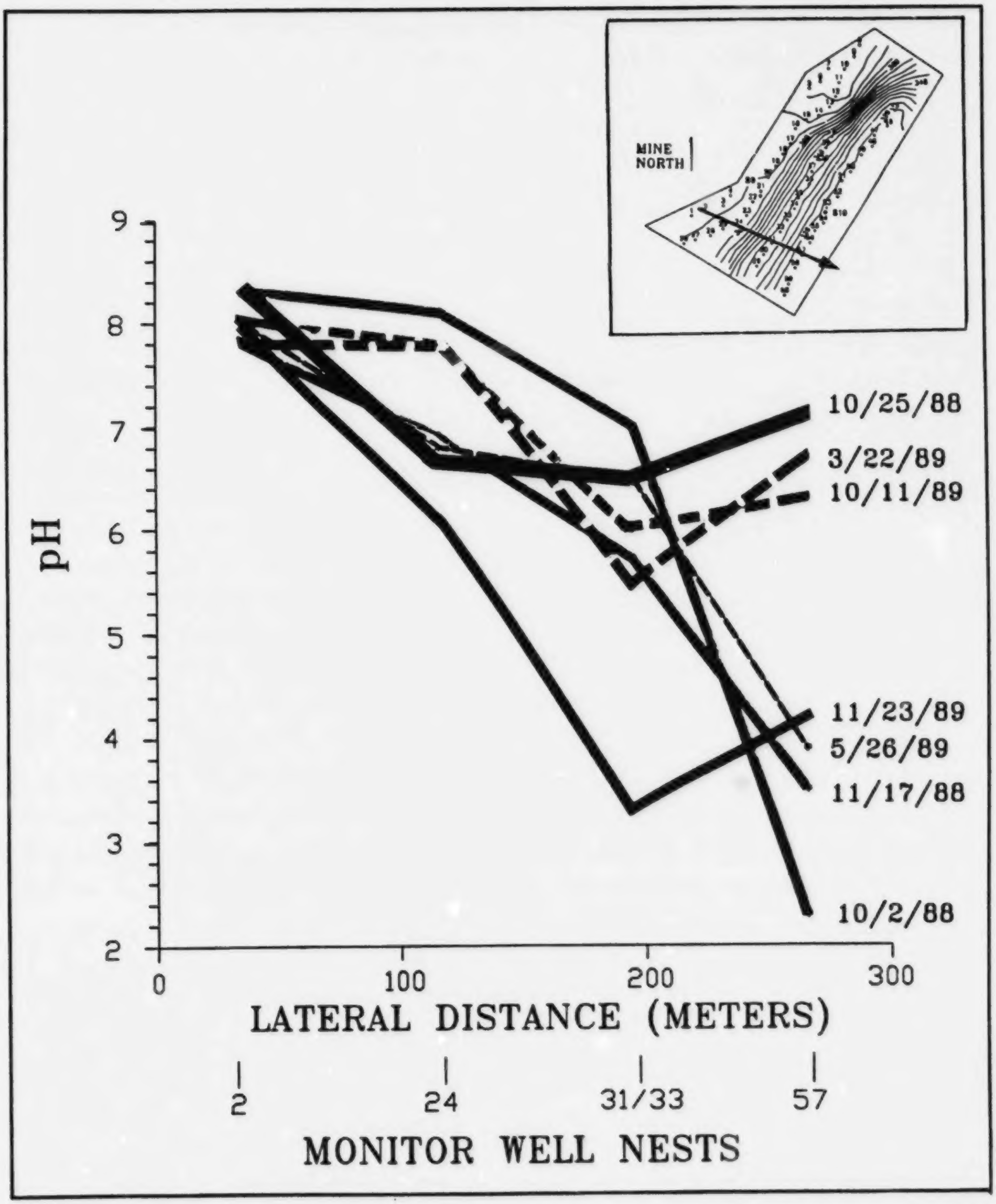


Figure 2.21 Spatial trends in groundwater pH in 1988 and 1989.

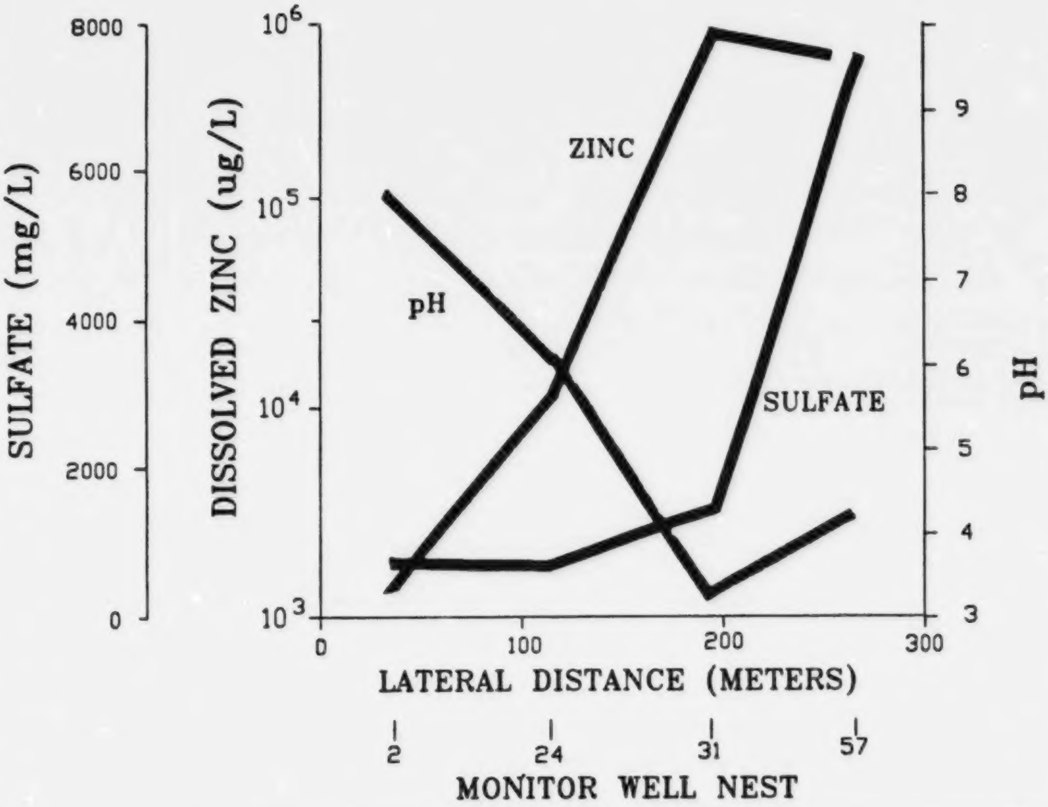


Figure 2.22 Spatial trends in groundwater chemistry in November 1989.

2.6 CONCLUSION

The main waste-rock dump at Westmin's Myra Falls operation has been generating acid drainage for at least a decade. In order to design reliable reclamation and decommissioning plans for minimizing environmental impacts, a detailed study was initiated on water movement, acid generation, and water chemistry within the dump. This report presents the information and interpretations based on data collected from 1981 to 1989.

Water moving through the dump originates from two sources: infiltration of precipitation on the dump surfaces and lateral discharge of background groundwater from the adjacent valley wall. The background groundwater flows through the base of the dump and the underlying bedrock towards the Myra Creek floodplain. Infiltration from the dump surfaces moves generally downward towards the water table and mixes with the background groundwater. Volume rates of infiltration appear to be negligible during dry months and significant during wet months, based on water levels in monitor wells and variations in water chemistry. The combined water appears to leave the dump below the toe and enter the floodplain sediments.

Proposed studies will further delineate water flow through the dump from the two sources as well as hydraulic interactions among the dump, adjacent dumps, the Lynx Pit, and the tailings impoundment. Reclamation plans will likely include groundwater controls to minimize and stabilize groundwater movement in and around the dump.

Acid-base accounting analyses of 230 borehole samples across the dump have shown that all of the waste rock on average is capable of generating net acidity. Additionally, a large portion of the neutralization potential in the rock has been found to be non-reactive or not available for neutralization. As a result of this non-availability and the long-term acid drainage in the area, most of the rock and sediment in the area are not capable of neutralizing acidity. The most active areas of oxidation and acid generation are within a 10-meter depth of exposed surfaces and in deeper zones where relatively high contents of sulfide minerals are located. Based on laboratory experiments, the rate of acid generation in the dump is on the order of 1-10 mg $CaCO_3$ equivalent/day/kg of rock.

Because there is little neutralization capacity in the rock, most of the neutralization observed in the dump is apparently derived from alkalinity in the background groundwater laterally discharging from the adjacent valley wall. When the acid zones are flushed by precipitation events, the acidic water flows downward to the water table and mixes with the neutral-pH groundwater. If acidity is less than approximately 100 mg/L, then pH will remain near neutral values due to the alkalinity, whereas, during wet months, the alkalinity is overwhelmed and acidic pH is found below the water table. Based on a generally defined flowpath through the western portion of the dump to the floodplain, pH consistently remains near neutral in the upgradient portion of the flow system near the valley wall, but fluctuates significantly near the toe. This is attributed to the progressive addition of acid water along the length of the flowpath.

The leaching of metals further degrades water quality in the dump. However, significantly elevated aqueous concentrations of metals are noted even in neutral-pH water. This may be a consequence of enhanced leaching or solubility by aqueous complexation, but further work is required to confirm this and to design controls for metal leaching.

Despite the flushing of acid zones, especially during wet months, general calculations suggest that most of the annual production of acidity is retained in the dump, and this acidity likely remains available for flushing. As a result, remediation and decommissioning planning must address either the neutralization of this acidity or the control of infiltration and water-table variation. Further work is planned to delineate in more detail the physical and chemical hydrogeology of the waste rock dump to develop reliable remediation and decommissioning plans.

3.0 CONTROL OPTIONS FOR AMD AT WESTMIN

Acid mine drainage results from both a chemical and biologically mediated oxidation process. The objective of acid generation control is to exclude or limit the key factors in the acid generation process, in particular those factors which control bacterial activity (specifically Thiobacillus spps.). Such control is preferable to control of resultant acid mine drainage. Consequently, attempts to control acid generation have focused on:

- biocidal control of the Thiobacillus population
- restriction of oxygen and water movement through the waste by use of surface covers and liners, and
- the use of neutralizing compounds (e.g., alkaline recharging).

Numerous biocidal agents have been shown to be toxic to Thiobacillus. Biocidal agents, such as anionic surfactants, could function for short-term purposes (e.g. Erickson *et al.*, 1985), however, the efficacy of these products, as used for coal wastes, may be limited in the treatment of waste rock. Other surfactants, particularly cationic products, may be more effective. The effects of heavy metals on Thiobacillus have been investigated (e.g, Tuovinen *et al.*, 1971; Imai *et al.*, 1975). The studies showed that Thiobacillus populations may rapidly adapt to increased metal concentrations and suggest that geochemical control of Thiobacillus using heavy metals is not considered feasible. Predatory organisms (rotifers and protozoa) have been tested for effectiveness in controlling Thiobacillus populations and field tests indicate their effectiveness to be unsatisfactory (McCready, 1987).

Application of surface covers such as topsoil or sewage sludge and subsequent revegetation of mine waste does not provide long-term control of acid generation (Bell, 1987; McCready, 1987). Liners and seals, if installed correctly are effective impermeable covers, however, the cost of utilizing synthetic liners over the Westmin waste rock dump is prohibitive. Furthermore, the limited practicality of liner application to waste rock piles and the limited potential for revegetating sloped, lined sites, renders the use of liners at the Westmin site questionable.

Surface application of limestone has shown some potential for controlling acid generation at sites with highly permeable surfaces and mildly acidic drainages (e.g. Ladwig *et al*, 1985; Caruccio and Geidel, 1987). Based on results of the waste rock dump study (Section 2), it is unlikely that this technique would provide adequate control at the Westmin Resources Myra Creek site.

Present technology does not provide a long-term solution to acid generation which would be suitable for use at the Westmin Resources Myra Creek site. Several approaches which offer some potential for control of acid generation include: evaluation of alternative bactericides; and, manipulation of the physical and chemical attributes of existing mine wastes (e.g. sludges and tailings) for the preparation of materials which can be used to seal waste rock surfaces to minimize air and water within the waste rock dump.

Treatment of acid mine drainage waters, which currently occurs at the Westmin site by the addition of lime, is not considered a long-term solution. Another treatment option involves the use of wetlands for acid control and metal removal, however, the process is not effective for control of all metals and huge wetland areas would have to be used to assure a minimum retention time in the order of 200 hours (Klusman and Machemer, 1989).

Therefore this study focuses on the evaluation of alternative bactericides and on the evaluation of surface sealants and/or grouting materials produced from cementitious mixtures incorporating mine waste materials for the control of acid generation.

4.0 BACTERICIDE EVALUATION

Column studies were initiated during 1988 to evaluate the use of biocidal alternatives to the anionic surfactant, sodium lauryl sulfate, which has been used previously for AMD control (Patterson, 1987). Cationic surfactants were suggested for evaluation on the premise that a higher degree of retention would occur with the negative surface charges found in waste rock.

However, only a preliminary evaluation of the effectiveness of cationic bactericide application was carried out. Results from the hydrogeological assessment of the Myra Falls waste rock dump indicated the need for control of acid generation at depth. Surfactant applications, regardless of toxicity to Thiobacillus, could only be used to control AMD within a very shallow depth of the waste rock dump (Patterson, 1984).

Subsequently, resources were reallocated to a more intensive evaluation of the use of solidified materials for AMD control. These efforts are described in Section 5.

4.1 Experimental Procedures

Six columns each containing one kilogram of crushed waste rock were prepared for evaluation of the effectiveness of a cationic surfactant, WSCP by Buckman Laboratories Ltd. to control AMD. The surfactant was selected on the basis of discussions with a technical representative of the surfactant manufacturer (Stewart, 1987).

Following a cycle of four weekly washes, a solution of 5 ppm surfactant was added to four of the six waste rock columns. The intent was that the two remaining columns would function as control columns. All columns were then subjected to a series of one week test cycles in which a small air flow was directed upward from the bottom of each column for a period of one week, followed by washing of each column with five 300 ml portions of deionized water. The washings were then analyzed for pH, alkalinity and acidity and conductivity.

4.2 Results and Conclusions

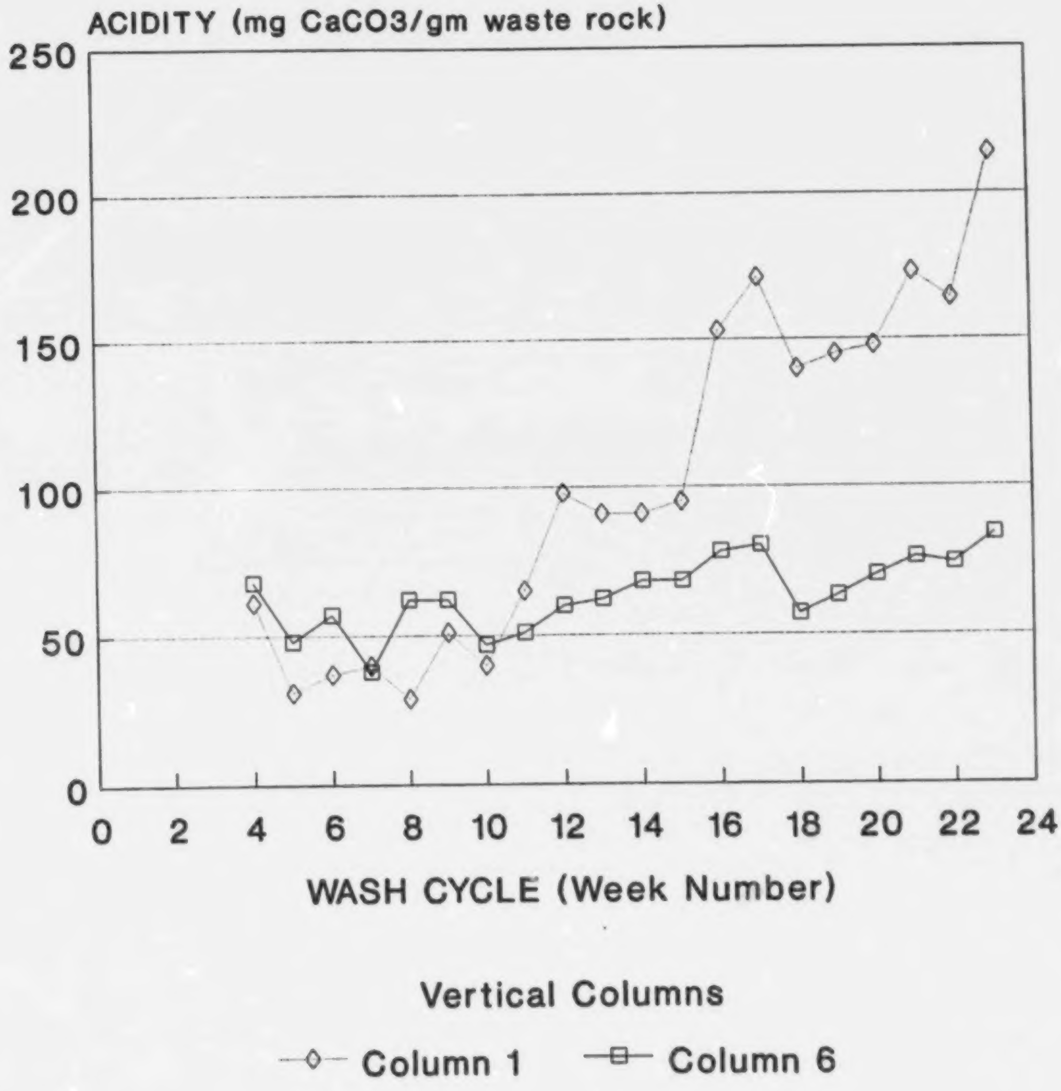
The variability in mineralogical composition and hence acid generation characteristics in the vertical columns limited the evaluation of the effectiveness of the cationic surfactant as an AMD deterrent. Nonetheless as shown in Figure 4.1, 4.2, 4.3, and 4.4 the results were not encouraging. Although decreases in acid generation are suggested, the continued AMD generation shortly after application is indicative of the transient nature of the bactericide (e.g. biodegradation or removal by infiltrating water) which puts into question the cost effectiveness of this approach.

The application of 5 ppm WSCP surfactant had varying effects on AMD production. Column #3 test results, shown in Figure 4.3, suggest AMD production was subdued for about 3 weeks after surfactant addition. Column #3 was the most active acid generating column. Test columns 1 and 2 were less active acid generators and AMD production was subdued for two to three months compared to normal AMD rates.

The biocide studies to this point were considered cursory.

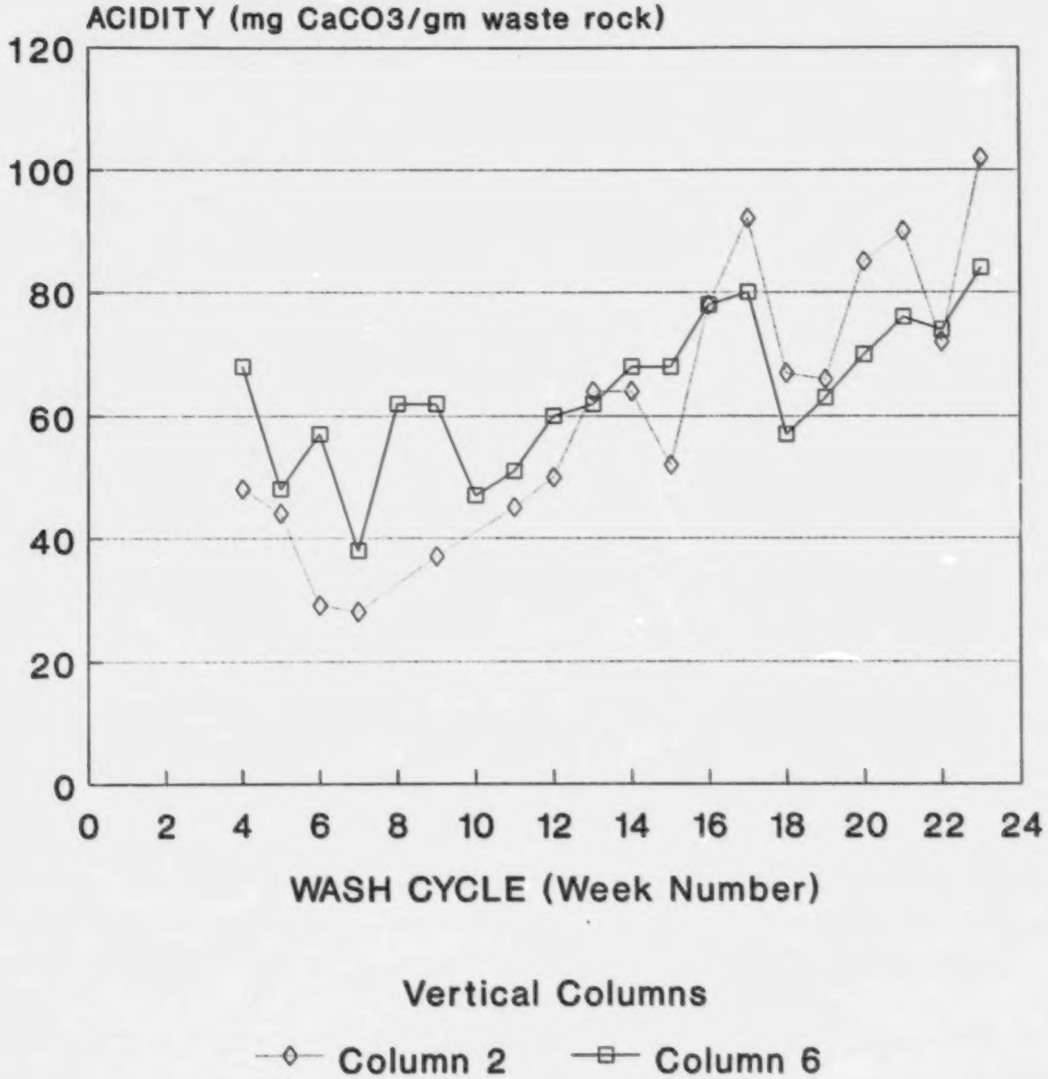
At this time, the results of the waste rock dump assessment became available and suggested that the oxidation zone of the Myra Falls waste dump is in excess of 10 meters. Based on Patterson's (1987) results which suggested that bactericide application is only effective at or near the surface of a waste rock dump and based on the fact that successful application of bactericide has only been documented for relatively shallow coal spoils (Kleinmann and Erickson, 1983; Sobek, 1987) this approach was terminated and resources were reallocated to enable a more intense study of the solidification approach.

Figure 4.1
Effect of Surfactant (WSCP) Treatment on Acidity - Column 1 vs Control



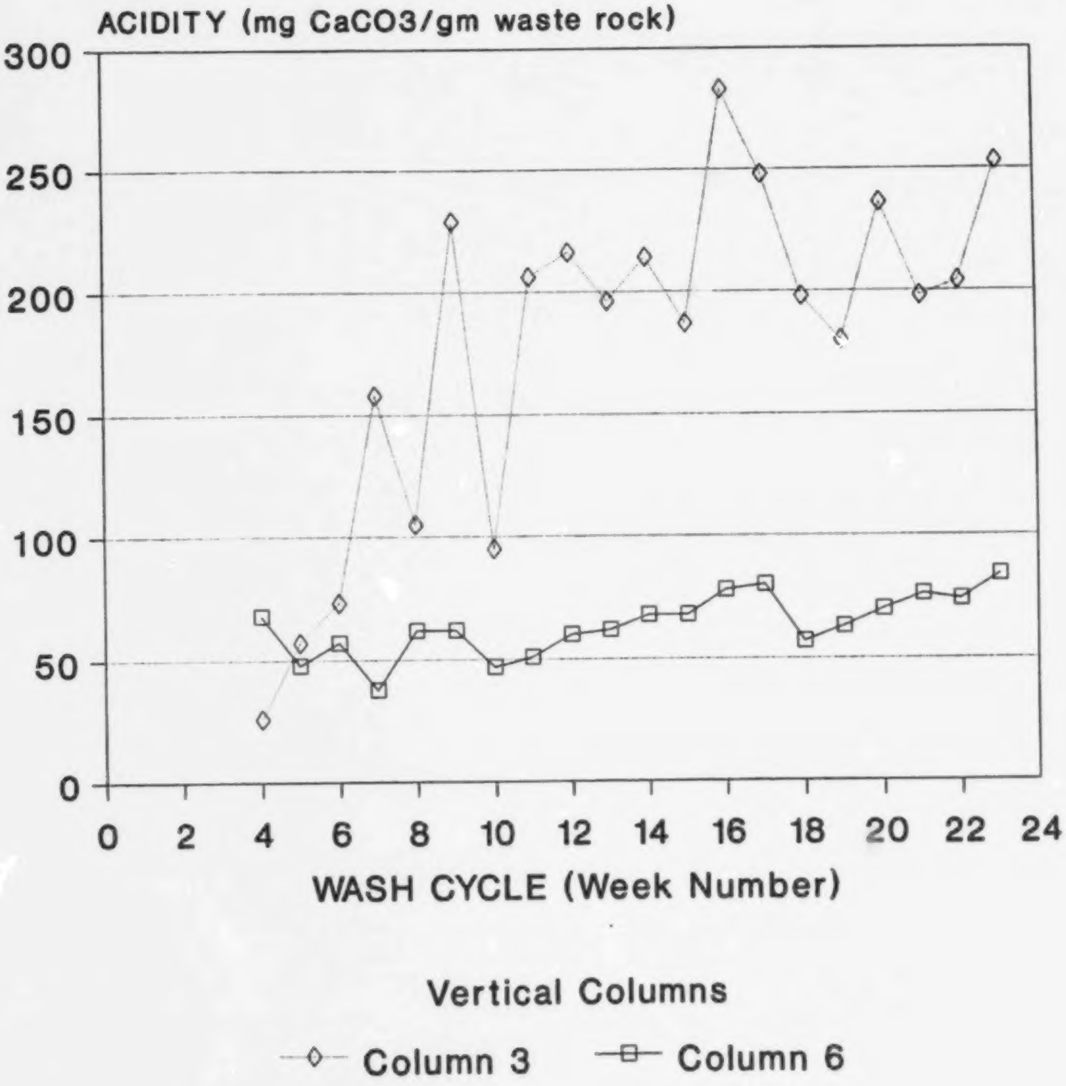
Columns 1-4 Treated With WSCP In Week 4
Column 6 Untreated Control

Figure 4.2
Effect of Surfactant (WSCP) Treatment on Acidity - Column 2 vs Control



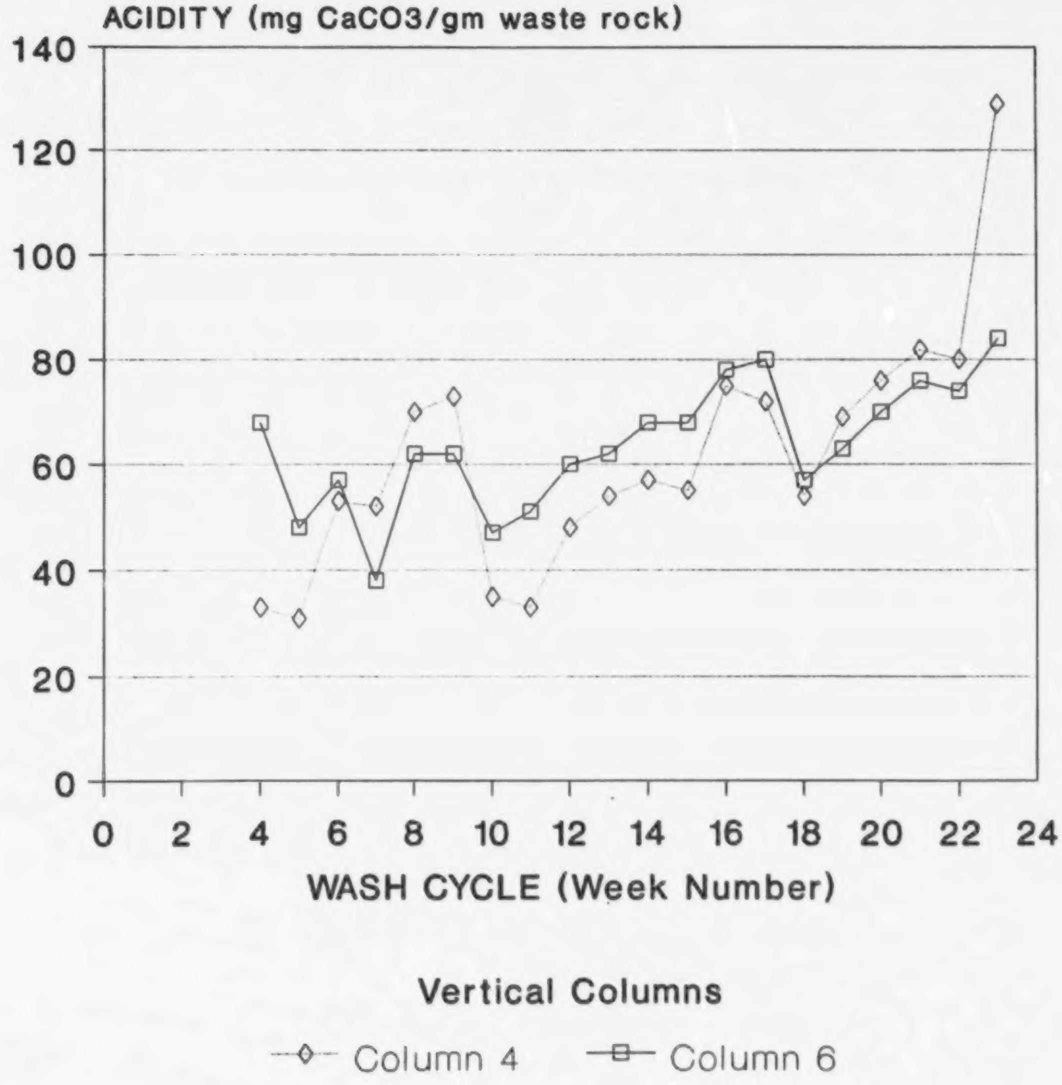
Columns 1-4 Treated With WSCP In Week 4
Column 6 Untreated Control

Figure 4.3
Effect of Surfactant (WSCP) Treatment on Acidity - Column 3 vs Control



Columns 1-4 Treated With WSCP In Week 4
Column 6 Untreated Control

Figure 4.4
Effect of Surfactant (WSCP) Treatment on Acidity - Column 4 vs Control



Columns 1-4 Treated With WSCP In Week 4
Column 6 Untreated Control

5.0 SOLIDIFICATION

The resiliency of Thiobacillus to chemical agents and difficulties in applying effective chemical agents in a waste rock dump suggest that the control of air and water availability is the most likely approach which could provide long-term control of acid formation in a waste rock dump. Numerous approaches have been attempted primarily by means of surface covers, such as plastic liners, till covers and asphaltic mixtures (Jones *et al.* 1982). The approaches have been hampered primarily by factors associated with cost and long-term efficacy.

Extensive research was conducted during the 1950's on the encapsulation of radioactive wastes within a solid material matrix to enable the burial of such wastes with minimal probability for release from the burial site. In the 1970's and 1980's the concept was extended for the disposal of inorganic wastes, where such wastes were mixed with materials such as cement, lime, fly ash, sodium silicate, and/or numerous additives to form stable solidified concrete-like materials which could be disposed safely in landfills. If mine waste products such as wastewater sludges and tailings could be integrated into a concrete-like geopolymer material, then the resultant product may be a potential surface sealant and a grouting material for the control of AMD from the Myra Falls waste rock dump. The approach if successful would enable the use of a wastewater sludge which otherwise would be subject to storage and disposal requirements of the B.C. Special Waste Regulation.

The use of the solidified material as a surface sealant and/or a grouting material for the control of AMD generation would require that the material:

- can be easily applied (i.e., good flow characteristics during application and an initial setting time greater than 2 hours but less than 12 hours);
- is durable (i.e., not subject to freeze-thaw effects and has reasonable strength to support a load and enable subsequent reclamation activities;
- is chemical resistant and cannot be readily affected by contact with oxidized rock and/or waters with low pHs;
- has low permeability to air and water;
- is economical compared to other sealing methodologies, and,
- is compatible with land reclamation efforts which will be initiated on the waste rock pile.

It was the approach of this study to evaluate the use of waste materials produced by the mine such as coarse and fine mine tailings and the wastewater sludges for the preparation of the solidification mixture. If other components were necessary, every effort was made to utilize local materials, for example, ground shale and sand as sources of alumina and silica.

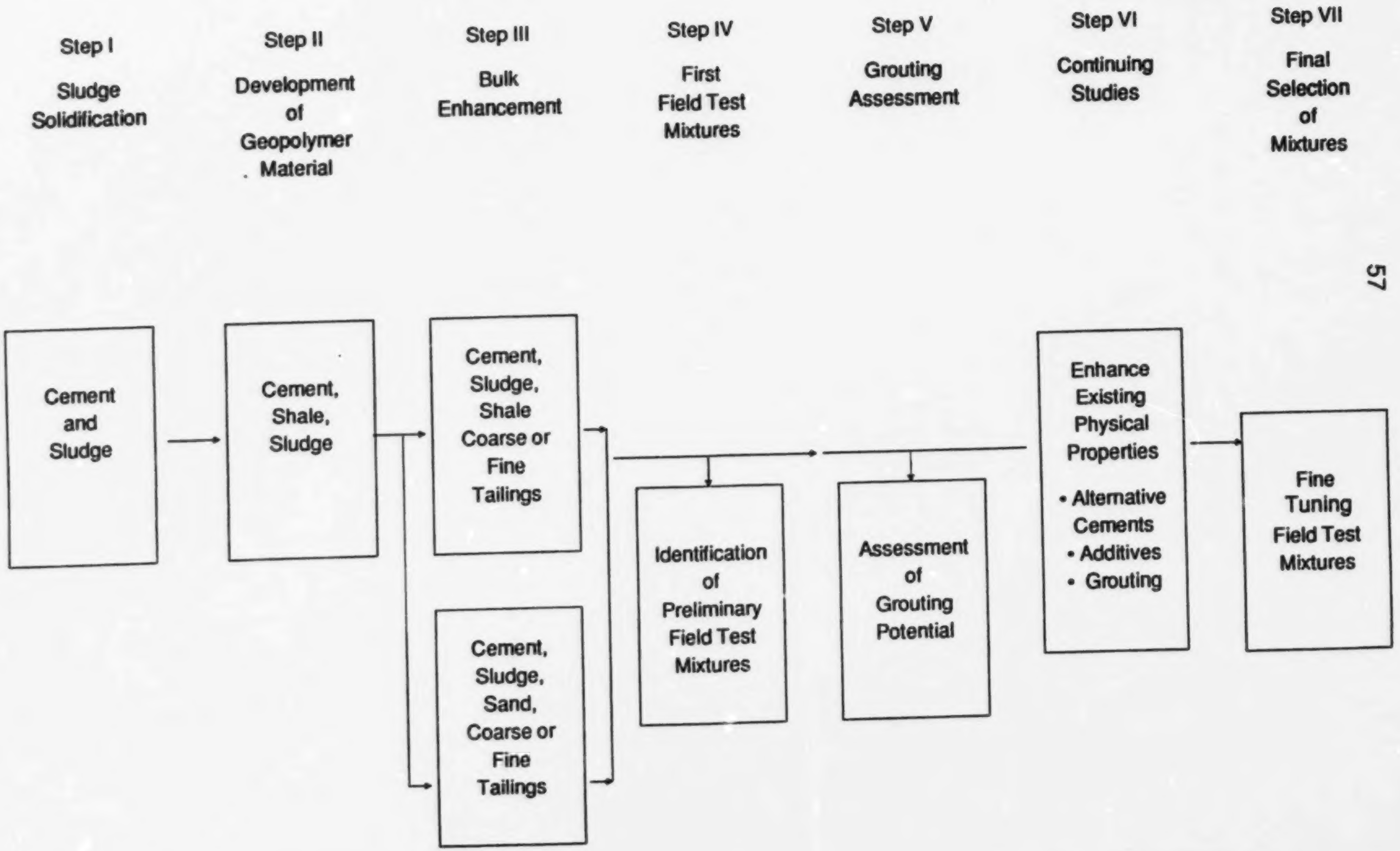
The laboratory approach was to systematically develop "best possible" solidification mixtures for subsequent field application. Figure 5.1 shows the overall approach which was used. Although the original intent was to evaluate the use of wastewater treatment sludge as a major component of the solidification material, the preliminary studies indicated that characteristics of the solid mixture such as strength and resistance to leaching had to be improved. Pozzuolana materials (aluminosilicates) were evaluated as additives to induce geopolymer reactions (Step II, Figure 5.1). Following results which suggested there is potential for geopolymer type reactions, efforts were made to determine whether the bulk of the material could be enhanced by use of mine tailings (Step III). The studies then focused on means to optimize the physical and chemical properties of the solidified mixtures. Details of the composition, physical and chemical properties of the test mixtures are provided in Table A-1 of the Appendix.

5.1 Laboratory Studies - Procedures

Preliminary laboratory studies were conducted to assess the feasibility of solidifying materials available at the Westmin site. The preliminary tests were limited to the determination of setting times, shrinkage, water permeability and leaching characteristics. Strengths were estimated on a 1-10 scale based on resistance to crushing where "10" would approximate the strength of construction concrete. After it became more evident that the approach was more promising, subsequent solidification testing was conducted according to documented laboratory procedures. The mixing and subsequent test procedures were carried out by use of a combination of procedures developed by the Environment Canada Wastewater Technology Centre for waste solidification and by the ASTM for concrete testing. There was a bias towards the ASTM procedures because the intended use would be more like that of a concrete material rather than a waste material which would be buried in a landfill without exposure to the open environment.

FIGURE 5-1

APPROACH USED FOR SOLIDIFICATION STUDIES


Step I
Sludge Solidification
Step II
Development of Geopolymer Material
Step III
Bulk Enhancement
Step IV
First Field Test Mixtures
Step V
Grouting Assessment
Step VI
Continuing Studies
Step VII
Final Selection of Mixtures
Cement and Sludge
Cement, Shale, Sludge
Cement, Sludge, Shale Coarse or Fine Tailings
Cement, Sludge, Sand, Coarse or Fine Tailings
Identification of Preliminary Field Test Mixtures
Assessment of Grouting Potential
Enhance Existing Physical Properties
• Alternative Cements
• Additives
• Grouting
Fine Tuning Field Test Mixtures

Materials: Solidification mixtures were prepared from a variety of materials on a weight basis. Originally, wastewater treatment sludge from the Westmin lime treatment settling ponds formed the main ingredient of the mixtures. An analyses of one batch of sludge is shown in Table 5.1.

Two types of cement were used for the evaluation tests: the common Type 10 cement and sulfate resisting Type 50 cement. "Fresh" quantities of the cements were obtained directly from the Canada LaFarge manufacturing facility in Richmond, B.C.

Other components such as sand and aggregate were obtained from local sources in Campbell River.

Fly ash, Type F, was obtained from Ocean Construction, and various concrete additives were obtained in small quantities from chemical suppliers in the Lower Mainland.

Both the fine and coarse fraction of Westmin mine tailings were used in the test mixtures. Bulk tailings are cycloned at the mine site to remove the coarse fraction, achieving a split of approximately fifty percent of fine to coarse tailings. Fine tailings are disposed in the tailings ponds and coarse tailings are used as mine backfill and as a drainage layer in the tailings ponds. Fine tailings consist of a grey-black, predominantly silt sized material with approximately 15% clay. Coarse tailings mainly consist of fine sand sized material with 15-20% silt content. Total sulfur concentration in fine and coarse tailings, respectively, is 2.4 and 3.4 percent. Elemental analysis and particle size distribution curves of Westmin fine and coarse tailings are shown in Table 5.1 and Figures 5.2 to 5.3.

Mixing: Weighed quantities of components were mixed by use of a rubber spatula in a stainless steel bowl until a consistent paste was formed. Mixing occurred for a further five minutes after achieving a consistent paste. Amounts of water added were measured and reported in terms of cement content.

Table 5.1: Elemental Analysis of Westmin Wastewater Sludge, Fine and Coarse Tailings*

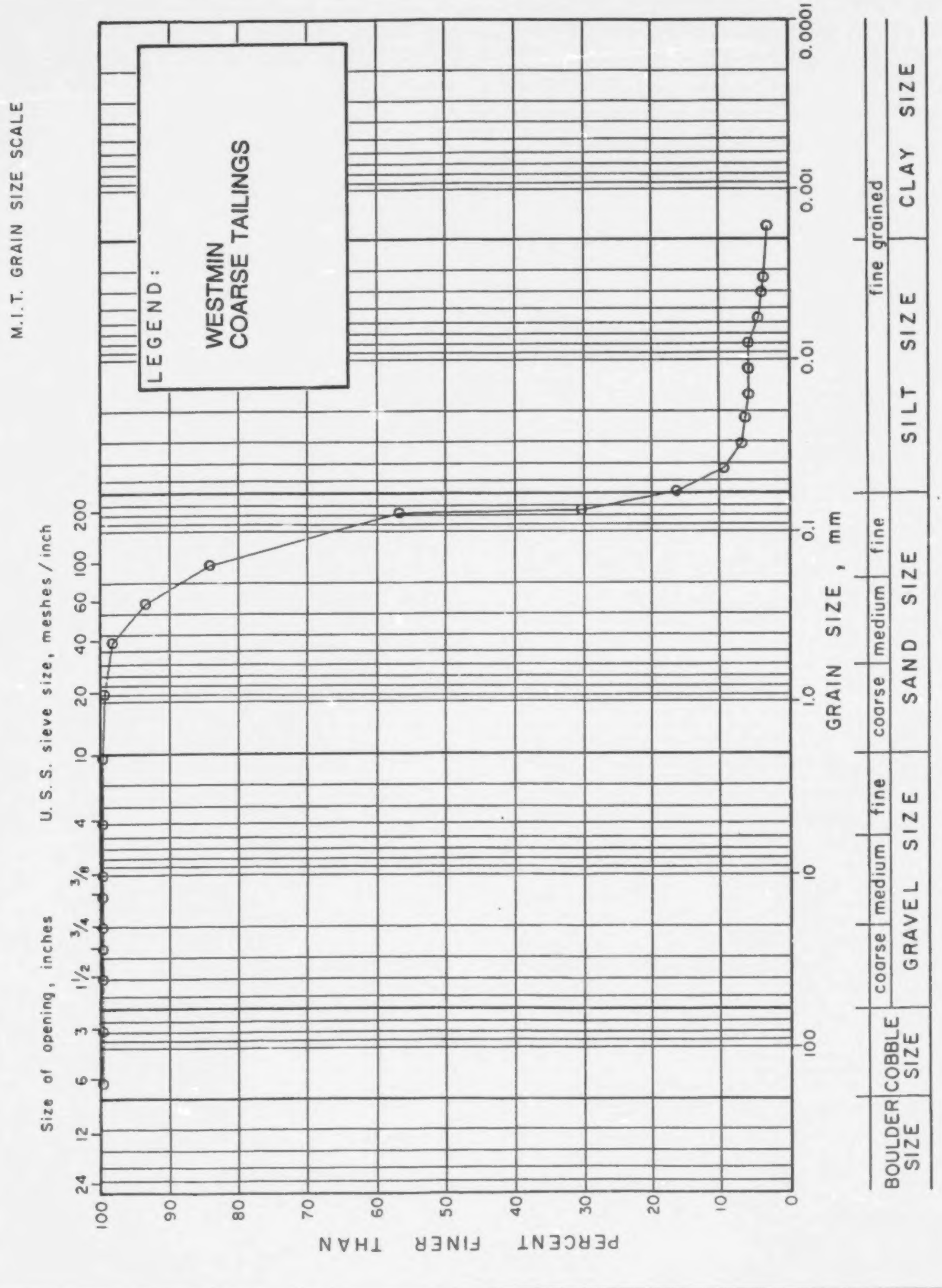
Metal	Wastewater Sludge	Fine Tailings	Coarse Tailings
Aluminum	58090	48732	2100
Silver	1.4	5.1	14
Arsenic	339	351	300
Calcium	168457	12038	37000
Cadmium	156	51.3	48
Chromium	4.5	<0.1	15
Copper	7326	1829	1600
Mercury	2.2	3.0	1.2
Iron	11684	226506	580000
Magnesium	65761	6054	4400
Manganese	30111	665	120
Molybdenum	7.7	50.7	59
Sodium	118	561	15.8
Nickel	170	95	82
Lead	168	149	940
Zinc	59030	15594	9600

* Concentrations are in ug/g (ppm).

GRAIN SIZE DISTRIBUTION

Figure 5.2

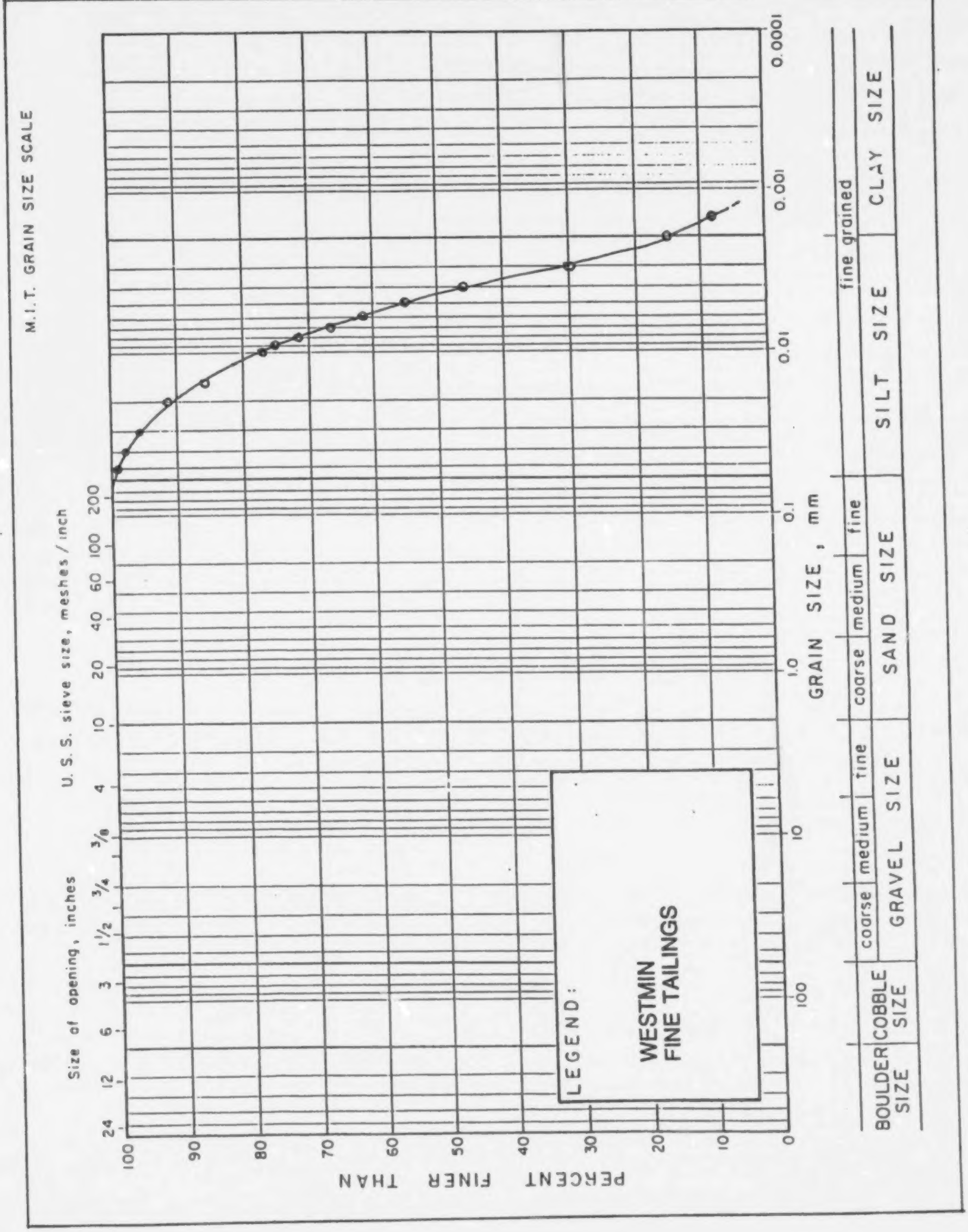
PROJECT NO 8921071 DRAWN .... REVIEWED .... DATE AUG-25-89



Golder Associates

GRAIN SIZE DISTRIBUTION

Figure 5.3



Set Times:	Setting times were determined by ASTM method C406. A conical form was filled with the blended mixture and the top smoothed with a spatula or trowel. The initial set was determined by two methods: the time at which a penetrometer would penetrate a distance of one inch with a pressure of 500 psi and by use of a Vicat apparatus. The final set was determined by means of the Vicat apparatus.
Compression Strength:	For preliminary samples, compression strength was estimated on a 1-10 scale based on resistance to crushing. Subsequently two inch cube molds were used for the preparation of cubes which were then sent for uniaxial compression testing by Golder Associates Ltd. in accordance to testing standards ASTM C87, C109, C141, C287, C396 and C593. The compression tests were carried out after 28 days of curing at room temperature in a closed chamber. On occasion 7 and 14 day compression tests were also conducted to evaluate strength versus time relationships.
Shrinkage:	Shrinkage was directly determined by measuring the linear dimension of a solidified block after 28 days of curing and comparing with the linear dimension of the two inch mold used to prepare the block.
Water Content:	The determination was carried out at 28+/-2 days after sample preparation. The samples were ground to 2 mm, weighed and placed in a drying oven at 60+/-3°C. The sequence of heating and cooling was continued until the mass change was no more than 0.1 gram.
Air Content:	An air void displacement method was used to determine air content in freshly mixed concrete. A Soil Test Model CT158 Concrete Air Indicator apparatus was used.
Slump Test:	ASTM Test Method C143 was used to determine slump in concrete. The test measures the original and displaced position of the center of the top surface of freshly mixed concrete after placing in a cone shaped mold and subsequently removing the mold.

Permeability: An adaptation of the falling-head procedure described by Environment Canada Wastewater Technology Center was used for this study. A chamber was constructed to contain a 1 cm X 1 cm X 0.5 cm sample of solidified material. Water was pressurized by use of a water column contained in a buret. For hydraulic conductivity, the pressure and flow rate were determined and the water permeability calculated in cm/s. One sample was submitted to Powertech Ltd. of Surrey, B.C. for water permeability testing using a high pressure method described by Hope and Malhorta (1984) .

Freeze-Thaw: Freeze-thaw tests were conducted for the assessment of physical integrity following a sequence of freeze/thaw cycles. Two inch cubes of 28 day cured mixtures were subjected to cycles of 24 hours at -4°C. followed by 24 hours submerged in water at room temperature (20+/-3°C.). Visual observations of structural integrity were noted.

Leaching: The solid sample was ground so that the aggregate particle size was no greater than 9.5 mm. Five grams of solidified material was added to an ehrlenmeyer flask. A solution of acetic acid and sulfuric acid at pH 3.0 was added so that the entire mixture was of 100 ml volume. A pH of 3 was selected as representative of acid drainage water to which the solidified mixtures may be exposed in the field. The mixture was then stirred for one hour (as per McLellan and Cote, 1988). The final pH was recorded and the liquid portion filtered and submitted for analyses.

5.2 Preliminary Studies: Solidification of Wastewater Sludges

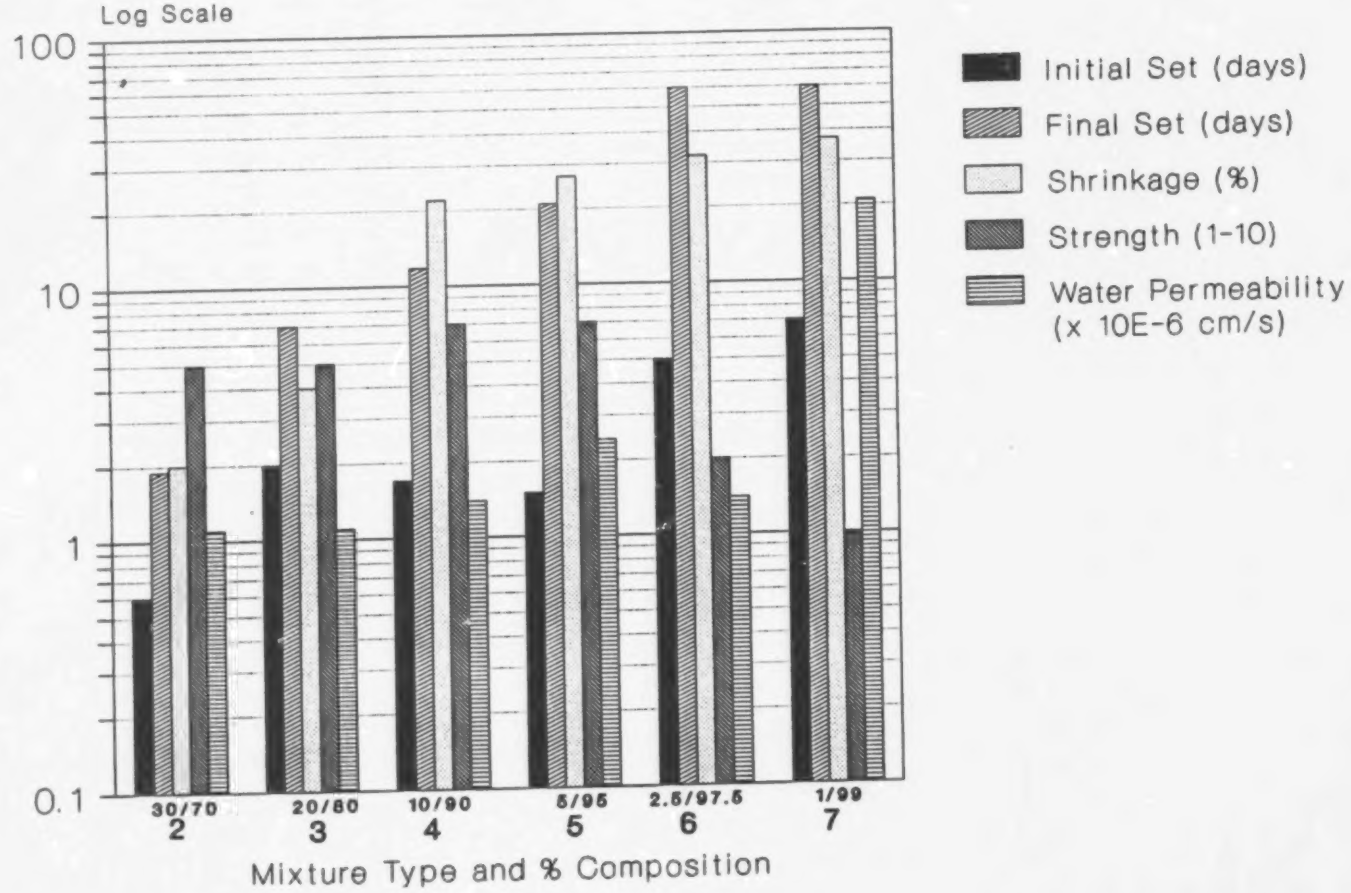
The solidification studies initially focused on the feasibility of using cement and wastewater sludges for the purpose of stabilizing the sludges and development of a waste rock dump sealant. Figure 5.4 shows some of the physical properties of solidified mixtures with varying cement:wastewater sludge ratios. Mixtures with 20 percent or less cement essentially failed to attain an initial set within a 24 hour period.

Figure 5.5 shows the various metal concentrations in leachates from the cement-sludge solidification mixtures exposed to water at pH 3. With reference to Figures A1 - A21 in the Appendix, it can be observed that leachate from all cement-sludge mixtures met leachate criteria for metal concentrations specified in the Westmin discharge permit from the B.C. Waste Management Branch (WMB), the Metal Mining Liquid Effluent Regulations and Guidelines (Environment Canada, 1987) and the B.C. Special Waste Regulation. The WMB discharge permit and Environment Canada Guidelines do not specify maximum values for aluminum and iron. However, if B.C. Special Waste effluent criteria are used for comparison then aluminum releases for all mixtures with the exception of the 30% cement: 70% sludge mixture were greatly in excess of the 0.2 ppm limit for aluminum. Iron releases for the 30:70 blend (mixture 2) of 3.5 ppm were considered high when compared to the CCREM (Canadian Council of Resource and Environment Ministers, 1987) limit of 0.3 ppm for protection of aquatic biota.

The studies showed that the wastewater treatment sludge from the settling ponds at the Westmin operation can be solidified solely with cement. Mixtures with a cement content of 30 percent produced a solid with some of the desirable properties required for use as a sealant, which included: shrinkage less than 2%, initial set greater than two hours but less than 24 hours, final set preferably within 48 hours but definitely no more than 72 hours, and low water permeability. However, low strength (hence durability) and leachate characteristics implied the need to investigate the use of additional solidification ingredients.

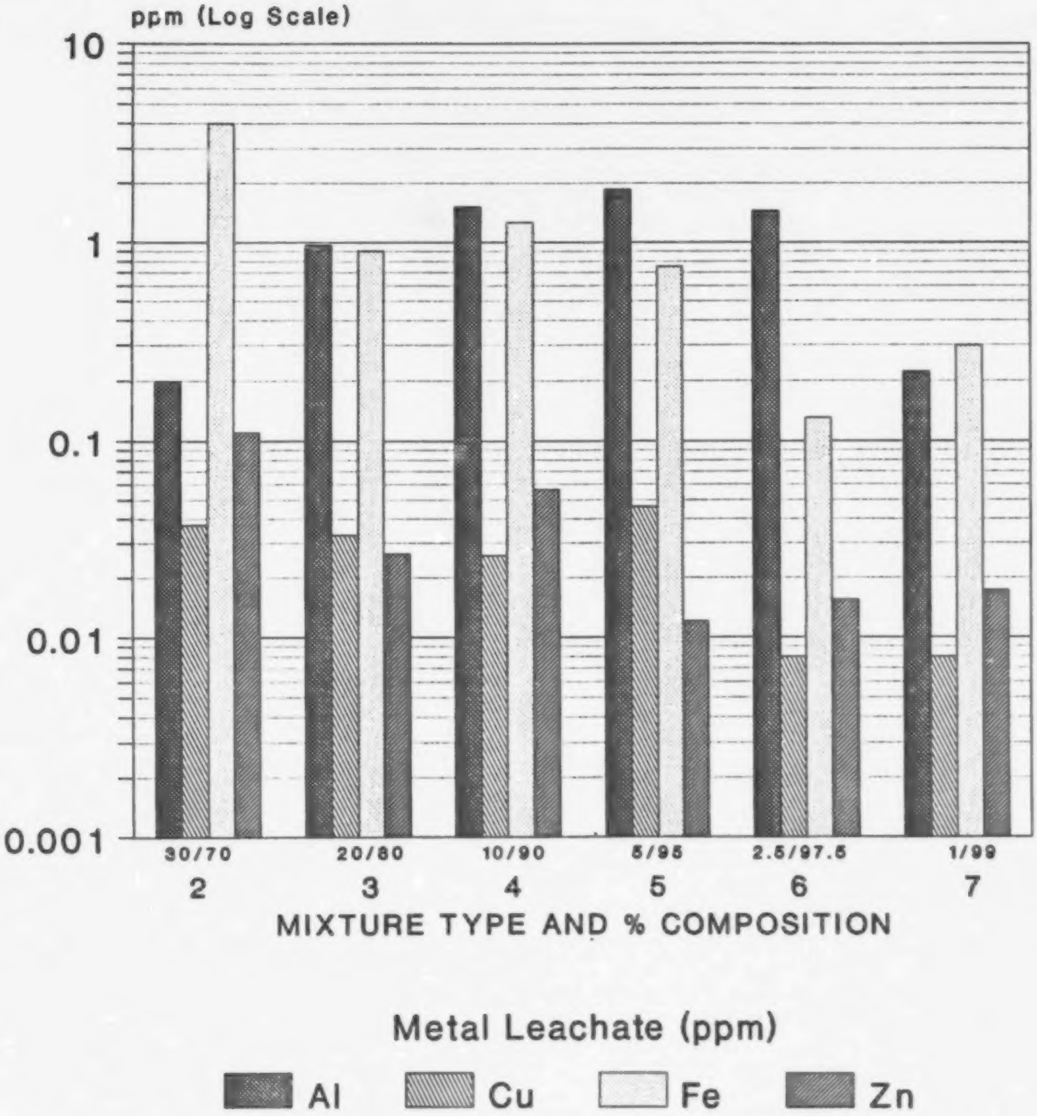
To determine whether solidification properties such as strength could be enhanced, and to determine whether factors such as set time could be reduced, the preliminary study then evaluated the addition of the following materials to the solidification mixture:

Figure 5.4
Comparison of Cement/Sludge Ratios



% Composition: cement/sludge

Figure 5.5
Comparison of Cement/Sludge Ratio Leachate Data



% Composition: cement/sludge

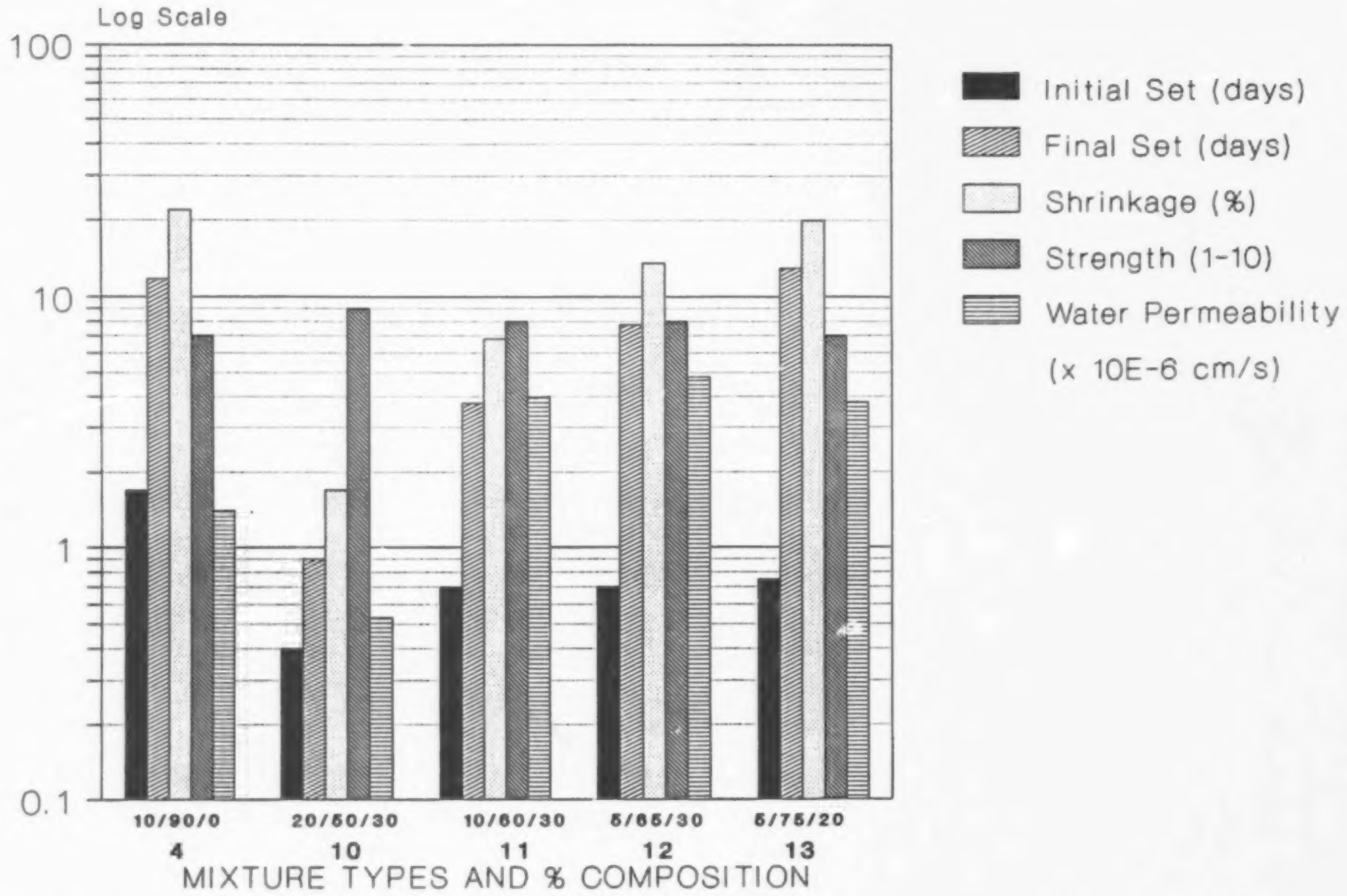
- Pozzuolana materials which are composed of alumino-silicates were added to encourage three dimensional polycondensation within the mixture. Shale, selected as a locally available alumino-silicate source, was found to marginally improve the physical properties of the mixtures by lowering set times to acceptable levels and improving strength. Mixtures 10 to 13 shown in Figure 5.6 illustrate the observed physical properties of the solid mixtures addition with the ground shale as a pozzuolana material. Despite improved physical properties, leachate tests continued to show high releases of aluminum from the mixtures (Figure A-1). Later studies, which evaluated the properties of mixtures containing cement, sludge, shale and coarse tailings, suggested that shale was not an essential ingredient.

- Tailings and locally available sand were added as aggregate to provide bulk to the solidified mixture. Tailings may also act as an additional source of pozzuolana material. The data in Figures 5.7 to 5.8 suggested that tailings had potential for use in the solidification process with coarse tailings being more preferable than fine tailings because of lower set times. The leaching data, however, still suggested excess releases of iron and aluminum from the mixtures (Figure A-1 and A-13 in the Appendix).

The preliminary tests also evaluated the differences in mixtures with and without sludge. With reference to Figure 5.8, it can be seen that with the use of 6% cement, the addition of sludge did not adversely affect set times and apparent strengths when compared with mixtures not containing sludge. Comparison of leachates showed that the presence of wastewater sludge had the following effects on leachate quality (mixtures 34 and 36 versus mixtures 42 and 44 in Figures A1 to A21): aluminum levels increased appreciably on occasion above regulatory limits; cadmium levels decreased; copper levels decreased appreciably; iron concentrations decreased; and zinc levels decreased. Overall, the presence of sludge did not significantly influence the physical properties of the solidification mixture. Therefore, the inclusion of sludge in the solidification mixtures offers a means of environmentally suitable disposal.

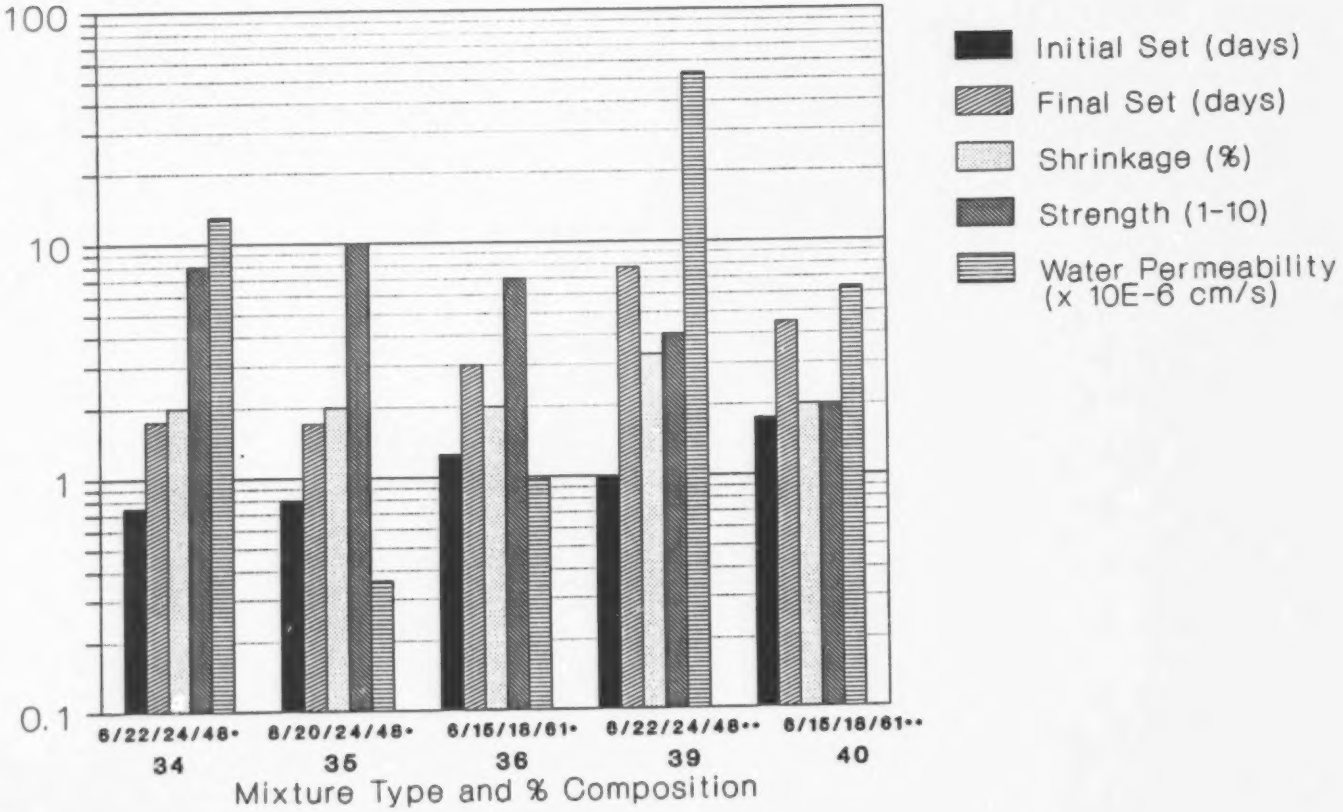
Figure 5.6

Comparison of Cement/Sludge/Shale Ratios



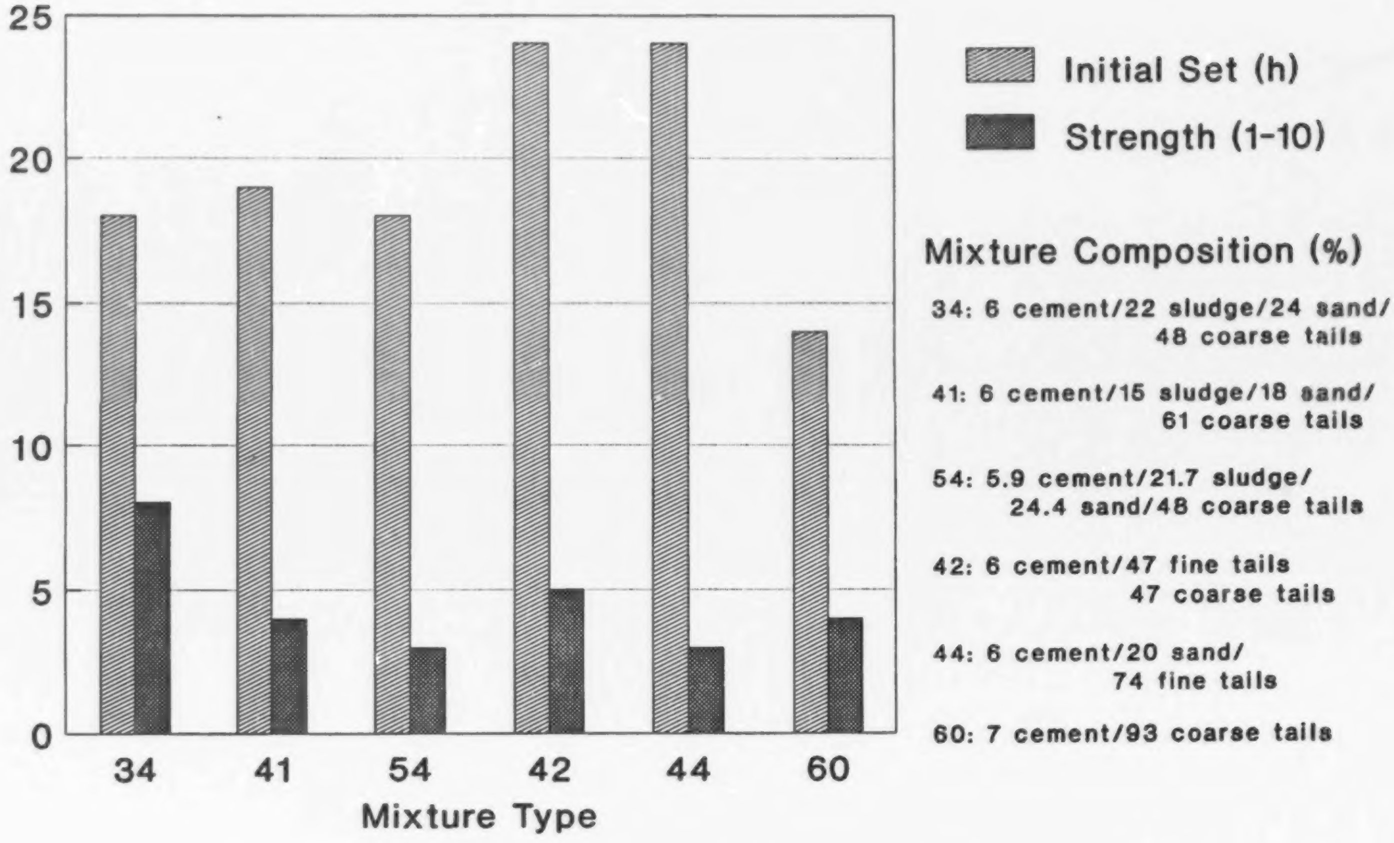
% Composition: cement/sludge/shale

Figure 5.7
Comparison of Fine versus Coarse Tailings



% Composition: cement/sludge/sand/
*coarse tailings **fine tailings

Figure 5.8
Evaluation of Mixtures With and Without Wastewater Sludge



A 14 day compression strength of 7 MPa for a cement/sludge/sand/coarse tailings mixture (mixture 35) and a 28 day compression strength of 11 MPa strength for a cement/sand/coarse tailings mixture (mixture 44), suggested that with further study, solidification mixtures using mine waste materials and locally available materials could be prepared with physical properties similar to those of concrete. This conclusion was further substantiated by use of preliminary field tests whereby three mixtures were applied to waste rock piles located at the Westmin facility. The field tests are described in Section 6 of this report.

Subsequently, a specific research program (Phase III) was developed which consisted of the following steps: 1) a detailed laboratory program that included quantitative assessment of the effect of the proposed constituents (i.e., cement, sludge, tailings, etc.) and mix proportions on physical and chemical properties of the solidified mixtures; 2) a field assessment program to evaluate various mixtures in actual use as surface sealants; and, 3) a pilot scale program to evaluate potential use of the solidification mixtures for grouting.

5.3 Optimization of Cementitious Mixtures

The preliminary studies described in Section 5.2 constituted Phase I and II of this program. The results suggested that cement and coarse tailings should be the principal constituents of the mixtures, and that the solidified mixture could also incorporate the wastewater sludge without detriment to physical and chemical properties. During Phase III, solidified mixtures were developed to evaluate the influence of material properties, mix proportions and the addition of various admixtures (air entrainment agents and strengthening agents) and supplementary cementing materials (fly ash, lime, wastewater sludge, soluble silicates) on physical and chemical properties of cured cementitious mixtures.

While the preliminary solidification study focused on the solidification of wastewater sludge, the Phase III study attempted to develop a solidified cement mixture which is the most economical and practical combination of readily available materials.

Variables which influence a concrete mix include:

- the texture and grading of the aggregate (e.g., tailings and/or sand)
- the percentage of aggregate used
- the water to cement ratio
- air content
- the use of supplementary cementing materials
- the use of admixtures

The test program was therefore designed to evaluate the effects of these variables. The program was initiated with the use of simple solidification mixtures composed of cement and tailings to define the role of physical factors such as water and air content and texture and grading. The program was then expanded to assess the addition of supplementary cementing materials and admixtures.

Tests conducted on solidified Westmin mixtures were selected on the basis of EPA (1986) specifications for stabilized/solidified waste as listed below:

EPA Specification	Test Conducted
Chemical Characteristics	
• leachability of waste components to contacting water	→ leachate test
• reactivity of solidified waste	→ net neutralization potential
Physical Characteristics	
• strength or bearing capacity	→ compressive strength.
• permeability	→ water permeability
• durability under conditions of surface exposure	→ freeze/thaw testing, field weathering of test piles

5.3.1 Water - Cement Ratio

The strength, durability and impermeability of a concrete depends to a large extent on the ratio of water to cement. Compressive strength of concrete is inversely related to the water-cement ratio. CSA Standard A23.1 and the Canadian Portland Cement Association provide guidance for selecting water-cement ratio's to meet various design conditions. To meet design conditions of frequent freeze/thaw and exposure to significant sulfate concentrations, water-cement ratio's ranging from 0.45 to 0.55 are generally used (CPCA, 1984). This range is based on non-air entrained concrete. This study used 10% cement: 90% coarse tailings to evaluate the impact of water:cement ratio with the use of coarse tailings as primary aggregate.

Figure 5.9 illustrates the compressive strength of 28-day mixtures with varied water-cement ratios. Lower water-cement ratios resulted in higher compressive strengths.

5.3.2 Cement Content

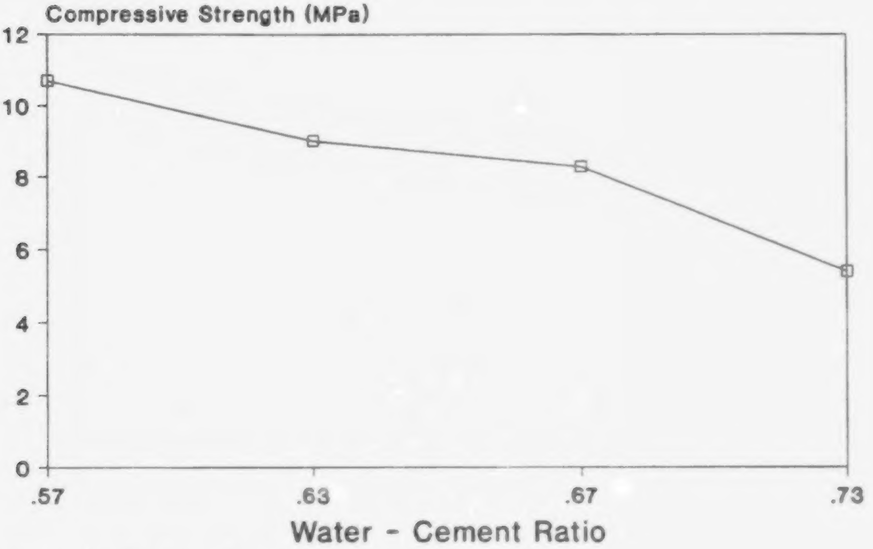
Although the quality of a cement paste is largely dependent on the water-cement ratio, an adequate amount of cement paste must be used to coat each particle of aggregate and completely fill the void space between aggregates with paste.

A series of tests were conducted to evaluate the proportion of cement required in a simple mixture containing only cement and coarse tailings. The quality of concrete was defined by the setting time and compressive strength of 28-day cured samples. The results, shown in Figure 5.10, illustrate that as the proportion of cement in the mixture increases the compressive strength also increases significantly while the initial set time progressively decreases until it reaches approximately eight hours.

5.3.3 Effect of Aggregate Particle Size and Distribution

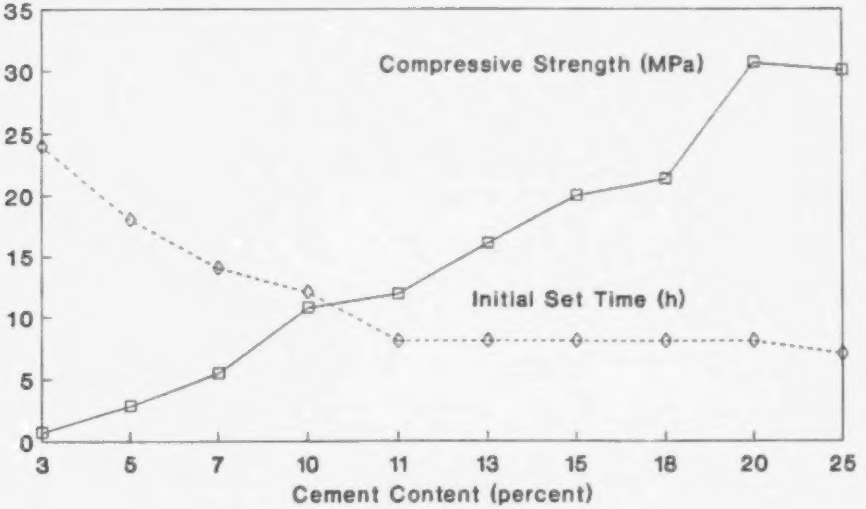
Aggregates in concrete mixtures are generally divided into two groups; fine and coarse. Fine aggregates consist of material with a coarse sand texture and finer textures, while material in the gravel size range (>2 mm) is considered coarse aggregate. The aggregates used in the test mixtures consisted of medium to coarse textured sand and mine tailings. The texture of fine and coarse mine tailings ranged from predominantly silt for fine tailings to fine sand for coarse tailings (Figures 5.2 and 5.3). Therefore, the test mixtures were representative of a mortar rather than a concrete mix. Mortar

Figure 5.9
Water - Cement Ratio vs Strength



Mixtures 61, 64, 65, 66

Figure 5.10
Strength and Initial Set Time
as a Function of Cement Content



mixes consist of cement and aggregate ranging in size from sand to finer material while concrete contains larger sized aggregate.

A series of test mixtures were formulated using 10% cement and 90% fine and coarse tailings to evaluate the effect of aggregate texture on solidification properties. The results, shown in Figure 5.11 indicate that for a constant cement content, increased particle size of the tailings shortens initial set time and improves compressive strength.

A subsequent series of tests evaluated the effect of particle size distribution of aggregates on cement and water requirements, workability, shrinkage, porosity and durability. The principle of using a collection of particle sizes in a mixture is based on most efficient and economical use of cement paste. A unimodal aggregate size will result in a larger percentage of voids, while combining more than one aggregate size will reduce the void content and less cement paste will be required to fill the voids. Figure 5.12 illustrates the effect of particle size distribution on set time and compressive strength of several test mixtures. A range of particle sizes as shown by mixtures 74, 75, 88 and 89 improves the 28-day compressive strength and lowers the initial set time characteristics of the cementitious mixtures as compared with mixtures 50 and 73 which contained only fine or coarse tailings as aggregate. Of interest was the observation that the range in particle sizes in the graded aggregate test mixtures (i.e., fine to coarse tails and coarse tails to sand) does not result in a significant difference in compressive strength or initial set time. However, further attempts to evaluate the effect of particle sizes on concrete properties showed that for a constant cement content, increasing the proportion of sand to the finer textured coarse tailings improved the compressive strength of the mixture (Figure 5.13).

5.3.4 Effect of Admixtures

The effectiveness of air entrainment and strengthening additives was evaluated for improvement of physical properties of the cementitious mixtures.

Air-entrainment admixtures increase the volume of air in freshly mixed concrete and the following property changes of the cementitious mixtures generally are observed:

Figure 5.11
Fine and Coarse Tailings Addition - Effect on Initial Set Time

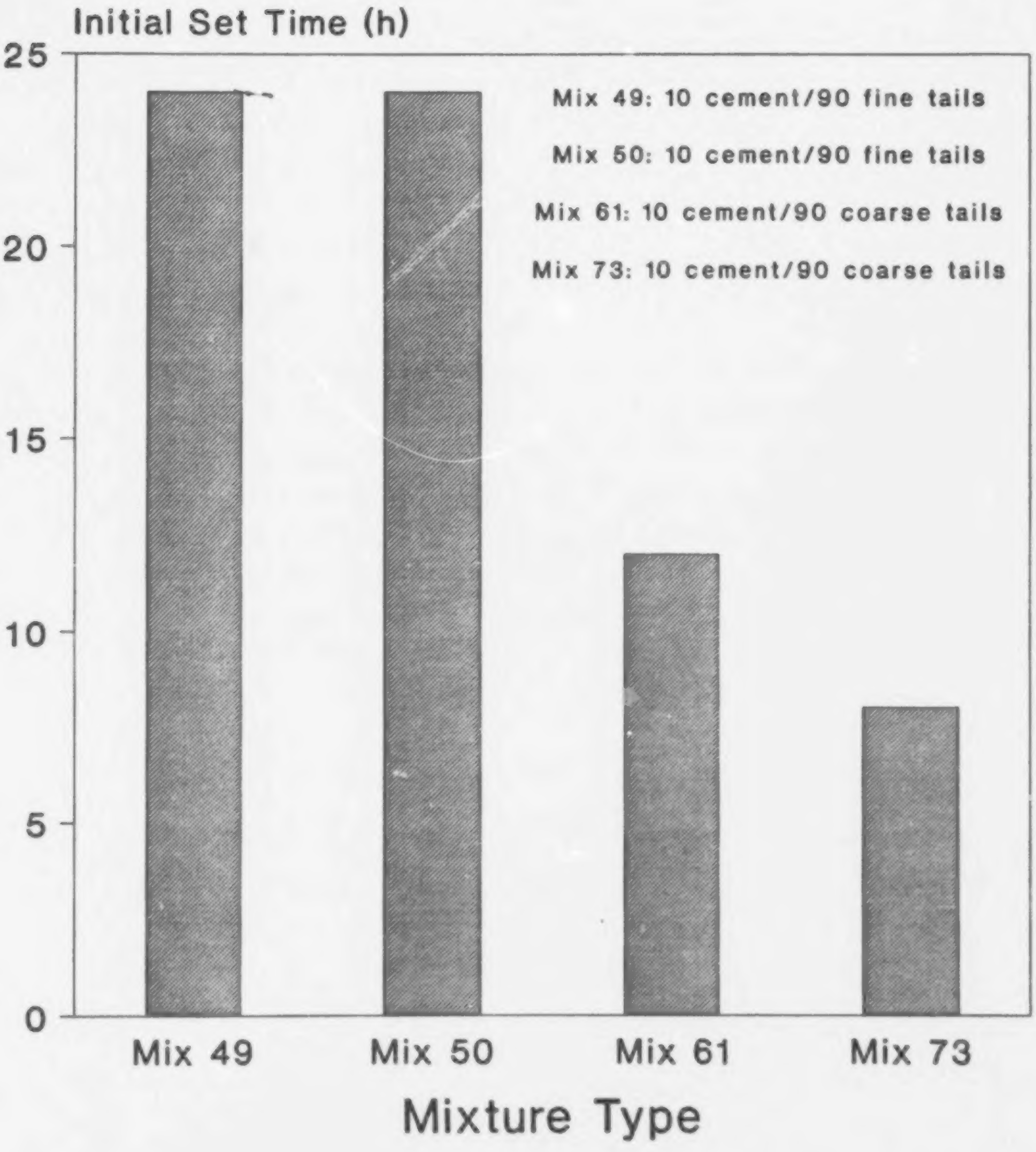


Figure 5.12
Effect of Particle Size Distribution
on Set Time and Strength

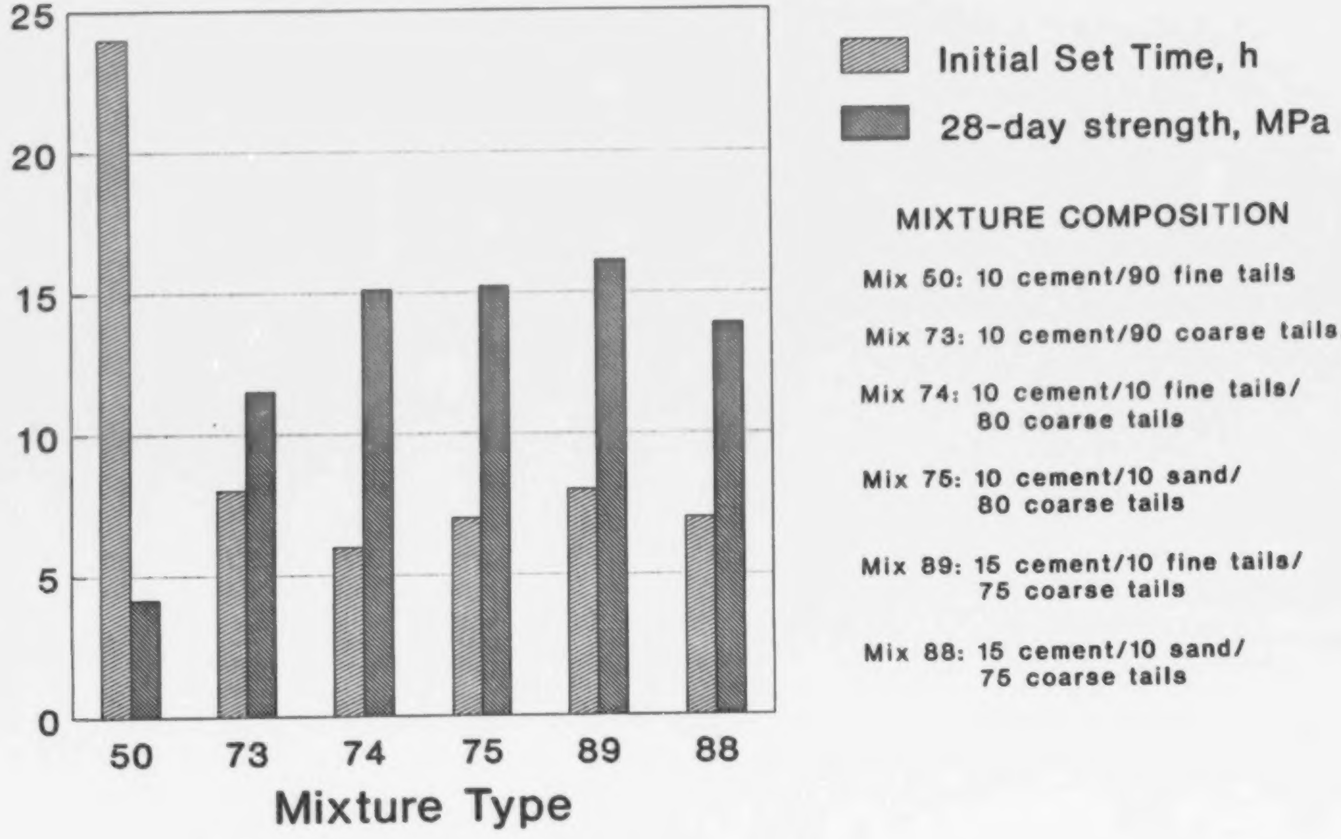
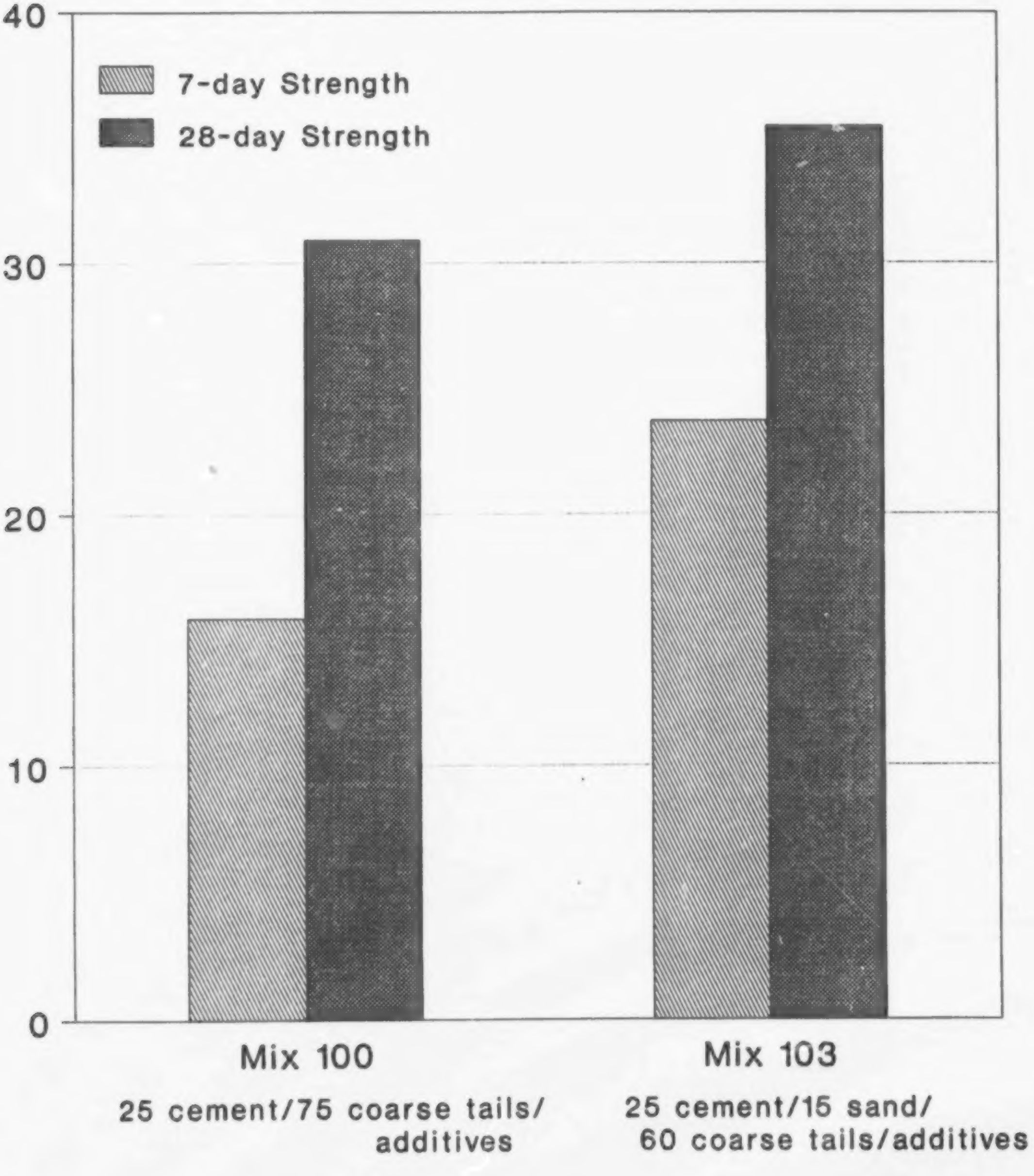


Figure 5.13
Aggregate Addition vs
7 and 28 Day Compressive Strength



- enhanced workability;
- less water is required to produce a mix of good workability;
- reduced segregation and bleeding in freshly mixed concrete;
- improved resistance to freeze/thaw effects (rupturing, cracking of hardened concrete);
- improved sulfate resistance; and
- improved watertightness (impermeability).

A decrease in strength can occur with a higher air content because the voids to cement ratio increases, but the loss is generally not significant.

Strengthening agents function by reducing the amount of mixing water required to produce a concrete of given slump. Figure 5.14 shows that the strengthening agent "Force 10,000", which is composed of silica fume, has a marked effect on compressive strength of the cementitious mixtures composed of 10% cement and 90% coarse tailings. Strength is increased over 200% beyond that achieved by the other strengthening agents. Other admixtures only marginally improved initial set time and compressive strength characteristics of the cementitious mixtures. Despite the significant effects of "Force 10,000" on compressive strength and reduced metal leaching, further studies with the additive were not conducted because of its high cost. Using "Force 10,000" would add a 200% increase in the overall material cost of the test mixtures.

Good durability was shown for mixtures with the addition of both air-entrainment and strengthening admixtures as shown in Table 5.2. The effect of the admixtures on 7 and 28 day compressive strength characteristics of the cementitious mixtures composed of 25% cement and 75% coarse tailings is shown in Figure 5.15. Early strength is higher for the mixture containing the strengthening agent, Daracem 100, as compared with the mixture containing only the air-entrainment admixture, Daravair. The mixture containing both admixtures had attained fully 97% of its 28-day compressive strength within the first 7 days of curing. The results indicate that the use of air-entraining and strengthening additives improves the strength and setting time characteristics of the cementitious mixtures. On the other hand, mixtures formulated without additives were also capable of achieving reasonable compressive strengths in the range of 15-25 MPa. Freeze-thaw test suggest that inclusion of strengthening agents significantly improves the durability of the cementitious mixtures. Durability tests (laboratory freeze-thaw tests and field studies) are ongoing and conclusions on durability could not be reached within the one year study period.

Table 5.2: Freeze/Thaw Resistance of Mixtures Containing Admixtures

Mix No.	Composition (%)	Freeze/Thaw Characteristics *Cycles	Integrity
56	8.5 cement/91.5 coarse tails/ no additives	24	Failed (cracked and spalling)
73	10 cement/90 coarse tails/ Daravair, Daracem	29	Good
77	10 cement/90 coarse tails/ Daravair, Daracem	21	Good
93	25 cement/75 coarse tails/ Daravair, Daracem	20	Good
100	25 cement/75 coarse tails/ Daravair, Daracem	15	Good

Figure 5.14
Additive Addition vs Strength

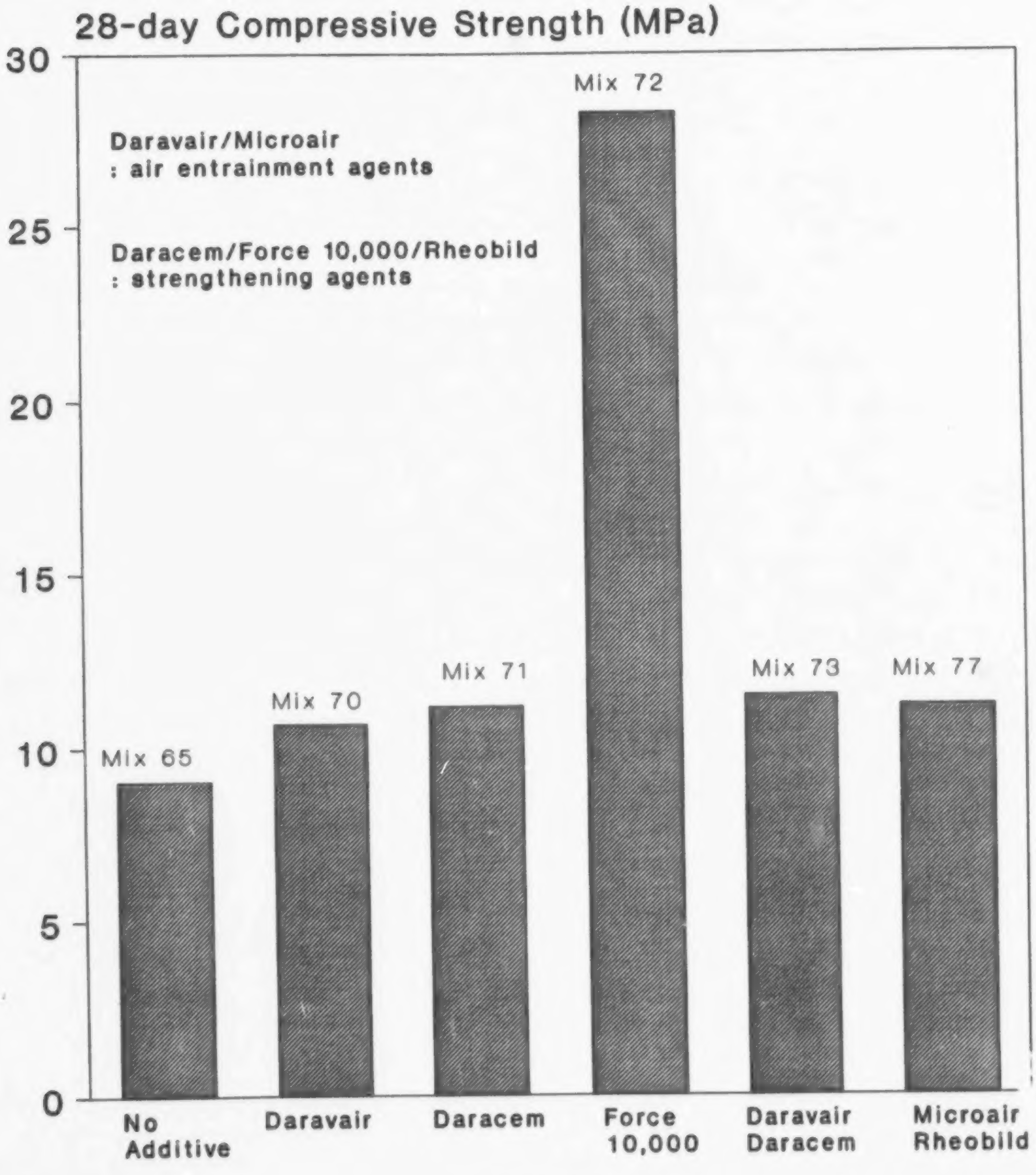
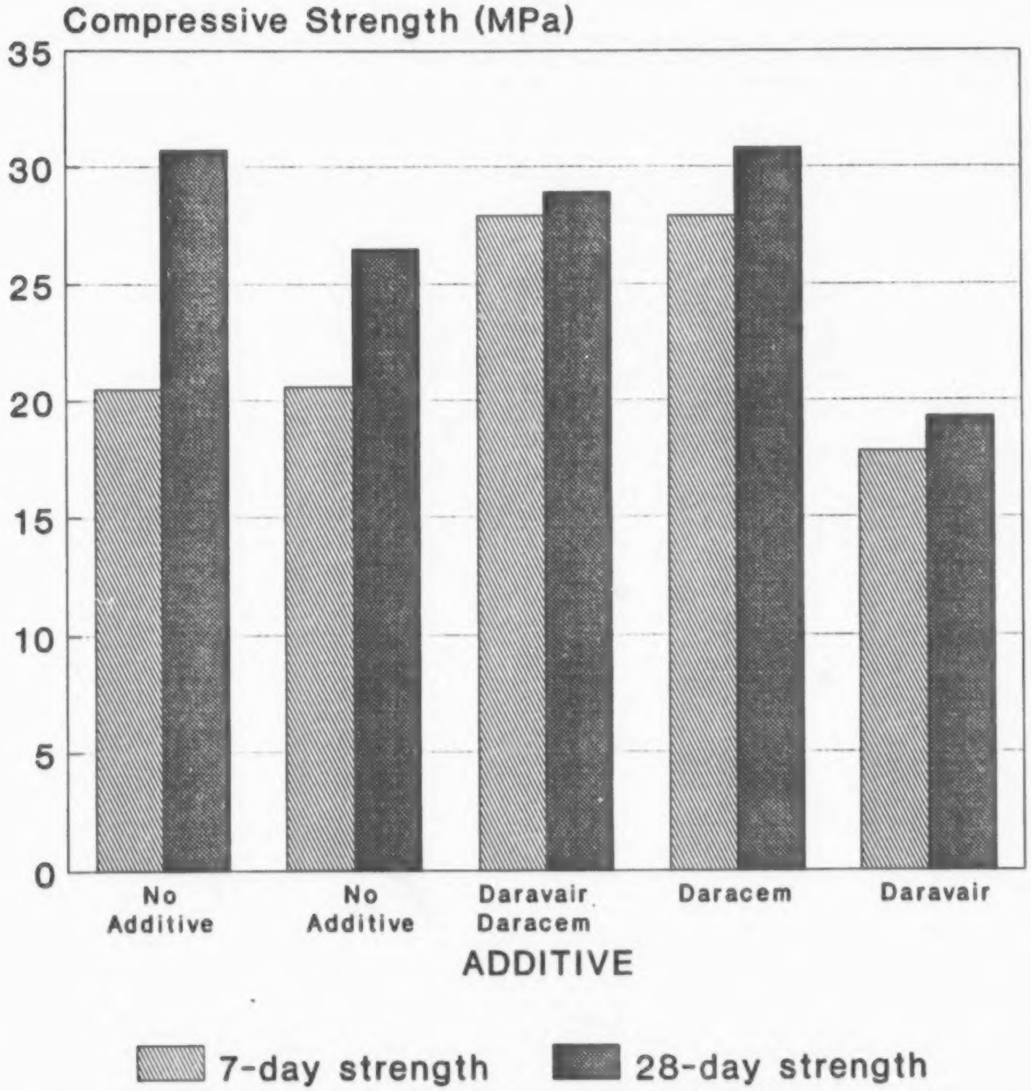


Figure 5.15
Additive Addition vs 7 and 28 day Strength



Mixtures 94-98
Composition(%) 25 cement/75 coarse tails

5.3.5 Effect of Additions of Supplementary Cementing Materials

Supplementary cementing materials are often used in conjunction with cement to enhance the properties of solidified materials through hydration and pozzolanic reactions. A series of test mixtures using fly ash, wastewater sludge, lime and soluble silicates were formulated to evaluate their effect on the properties of cementitious mixtures. Fly ash and soluble silicates are typical pozzolans which chemically react with lime ($Ca(OH)_2$) released during the setting of cement to form compounds with cementitious properties (CPCA, 1984). Addition of lime to a cement mixture raises the pH and the reaction temperature and is therefore used to lower the set time of a cementitious mixture.

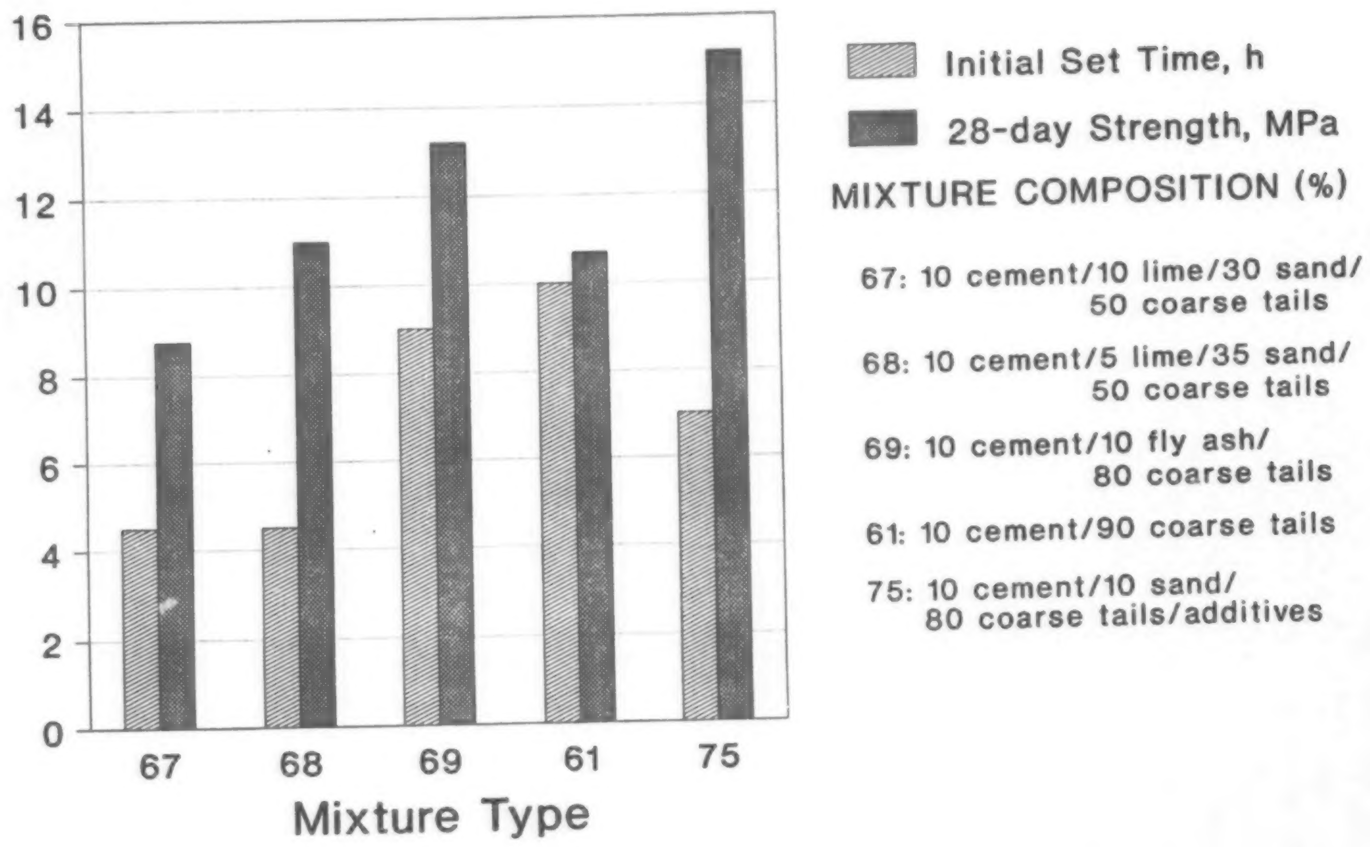
Figure 5.16 shows the effect of lime addition on set time and compressive strength on mixtures composed of cement, sand and coarse tailings. The addition of lime significantly reduced the initial set time as compared with mixtures containing fly ash and no supplementary cementing material. However, the higher rate of lime addition (10%) also lowered the compressive strength of the test mixture. In addition, an initial set time on the order of 4 to 5 hours may be too low for certain applications (i.e., trucking mixed concrete long distances).

Another series of test mixtures was designed to compare the effects of sludge and lime addition on setting time and strength properties of mixtures with a constant cement content. The basis of the comparison is that the sludge contains a high content of lime which is added in excess to the acid mine drainage waters for treatment. The mass of sludge and lime added was also consistent (mass of sludge is 10% of wet weight used). The results, shown in Table 5.3., indicate that addition of sludge retards initial set time while addition of lime accelerates the initial set time. The effect on compressive strength however, appears to be controlled to a greater degree by the proportion of cement in the mixture than by the addition of lime or sludge. At the lower content of cement (mixtures 54 and 78) low compression strengths were noted for the mixture containing sludge. The high water content of the sludge may have been responsible for the lower compression strength. At higher cement contents (i.e., 13 to 15%) sludge did not affect the strengths of the mixtures, however, initial set times were increased when compared to the other test mixtures shown in Table 5.3. Addition of sludge, even in low quantities offers an option for disposal of the sludge.

Table 5.3: Effect of Sludge and Lime Additions on Setting Time and Strength Characteristics of Cementitious Mixtures

Mix No.	Composition (%)	Initial Set Time (h)	28 - Day Compressive Strength (MPa)
54	5.9 cement/21.7 sludge/24.4 sand/48 coarse tails	20	1.7
78	5.9 cement/2.6 lime/30.5 sand/61 coarse tails	5.5	6.7
86	14 cement/0.7 lime/85.3 coarse tails/additives	8	21.5
87	14 cement/7 sludge/85.3 coarse tails/additives	15	19.1
81	13 cement/87 coarse tails/additives	8	16
82	15 cement/85 coarse tails/additives	8	19.9

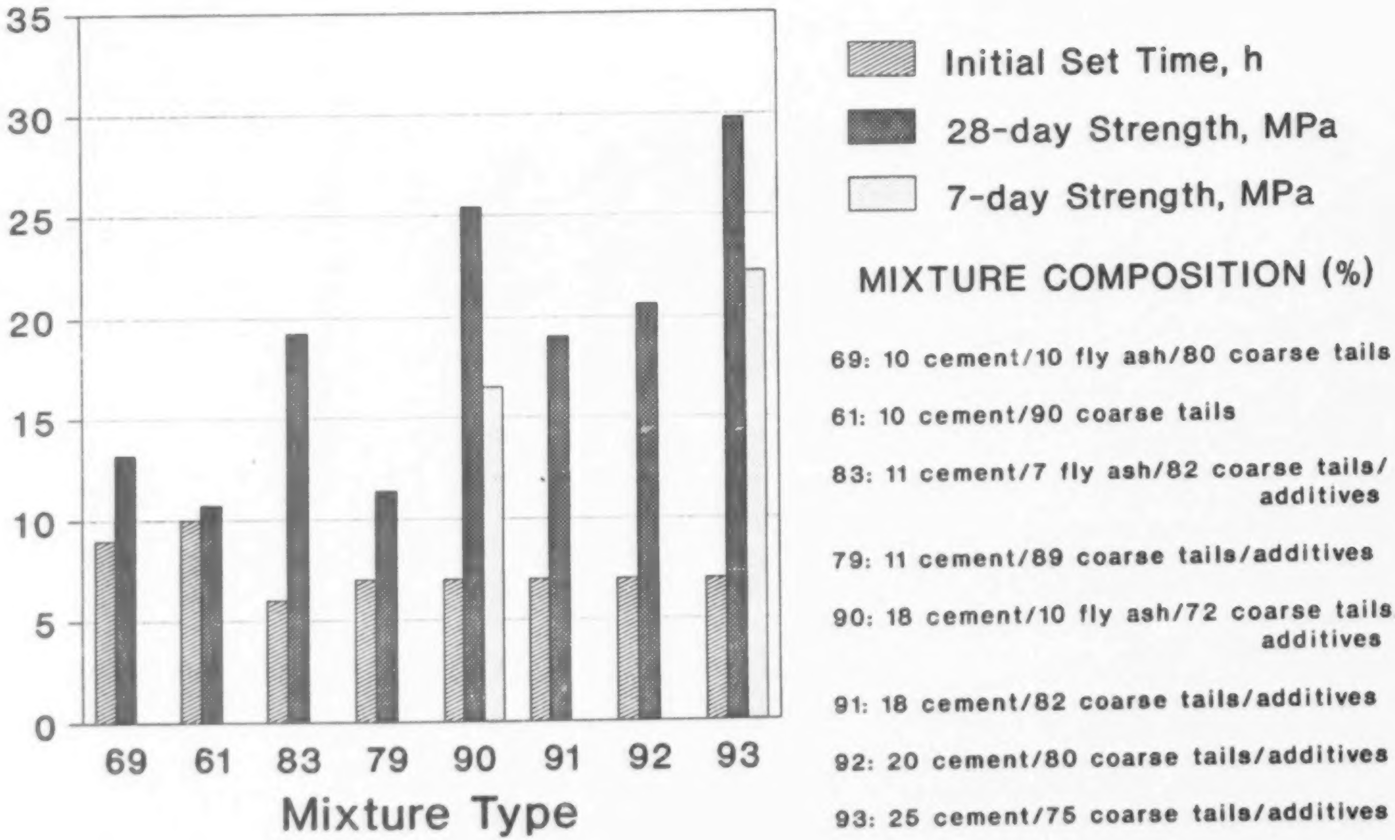
Figure 5.16
Effect of Lime Addition on
Set Time and Compressive Strength



The effect of fly ash on set time and strength is shown in Figure 5.17. Fly ash does not appear to influence the setting time of the cementitious mixtures. All initial set times are in an acceptable range between 6 to 12 hours. The results indicate that mixtures containing fly ash appear to have higher 28-day compressive strengths as compared with mixtures with equivalent cement contents (mixtures 69 vs 61; 83 vs 79; 90 vs 91). However, when comparing the properties of mixtures containing fly ash the equivalent total amount of cement only must be considered (i.e., total cement equivalent = cement plus fly ash), since the rationale for using supplementary cementing agents is to replace part of the cement requirements with these materials. Evaluation of the data in Figure 5.17 shows that, in general, for an equivalent total amount of cement only, test mixtures containing cement, fly ash and tailings have lower 28-day strengths than mixtures containing only cement and coarse tailings (mixtures 69 vs 92; 83 vs 91; 90 vs 93). In addition, the rate of strength gain with time of cementitious mixtures containing fly ash is often lower than that of equivalent mixtures containing only cement. Figure 5.17 shows the 7 and 28 day strengths for mixture 90 which contains fly ash and mixture 93 with cement only. Mixture 93 attains 74% of its 28-day compressive strength within the first 7 days of curing while mixture 90 attains 65% of its 28-day strength within a 7 day time frame. The use of fly ash as a supplementary cementing agent therefore does not appear to be warranted on the basis of enhancing the properties of the cementitious mixtures. The cost effectiveness of replacing a portion of cement in the mixtures with fly ash will be discussed in section 5.3.7.

Soluble silicates are often used to "flash set" cementitious mixtures. The effect of soluble silicates on the set time and strength of test mixtures is shown in Figure 5.18. The set time is significantly reduced with the addition of soluble silicate. A set time of 3.5 hours will imply the need for on-site preparation. Addition of soluble silicate did not improve the 28-day strength beyond that achieved with cement and coarse tailings. Therefore, the addition of soluble silicate is not a requirement for the test mixture except in applications where short initial set times are required (i.e., shotcrete).

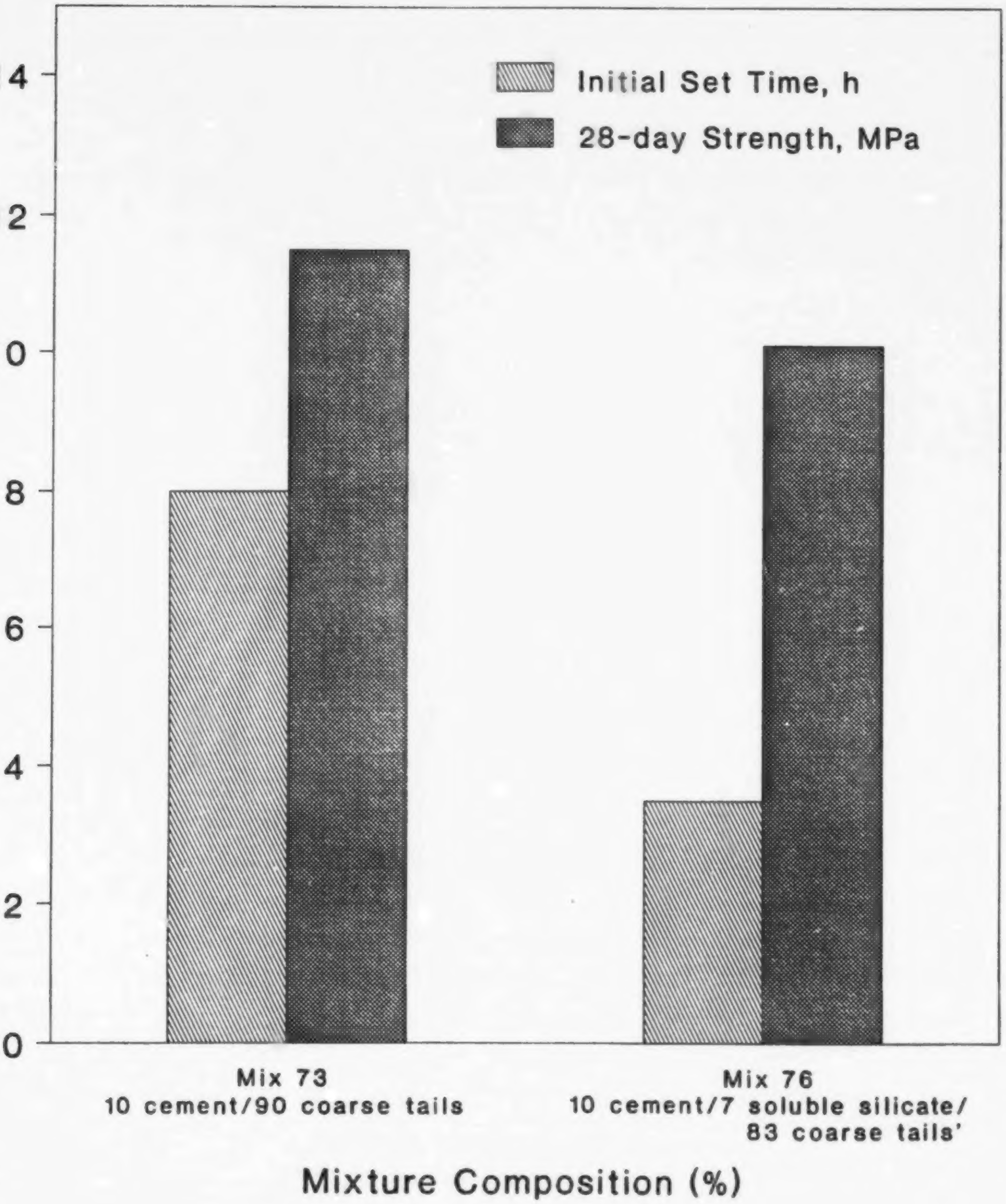
Figure 5.17
Effect of Fly Ash on
Set Time and Strength



MIXTURE COMPOSITION (%)

69: 10 cement/10 fly ash/80 coarse tails
61: 10 cement/90 coarse tails
83: 11 cement/7 fly ash/82 coarse tails/additives
79: 11 cement/89 coarse tails/additives
90: 18 cement/10 fly ash/72 coarse tails/additives
91: 18 cement/82 coarse tails/additives
92: 20 cement/80 coarse tails/additives
93: 25 cement/75 coarse tails/additives

Figure 5.18
Effect of Soluble Silicate on Set Time and Strength



5.3.6 Chemical Characteristics

Chemical stability of the cementitious mixtures is a measure of the environmental suitability of the material. Because the test mixtures contained mine tailings as a major ingredient, the reactivity of the hardened mixture as determined by acid neutralization potential was measured.

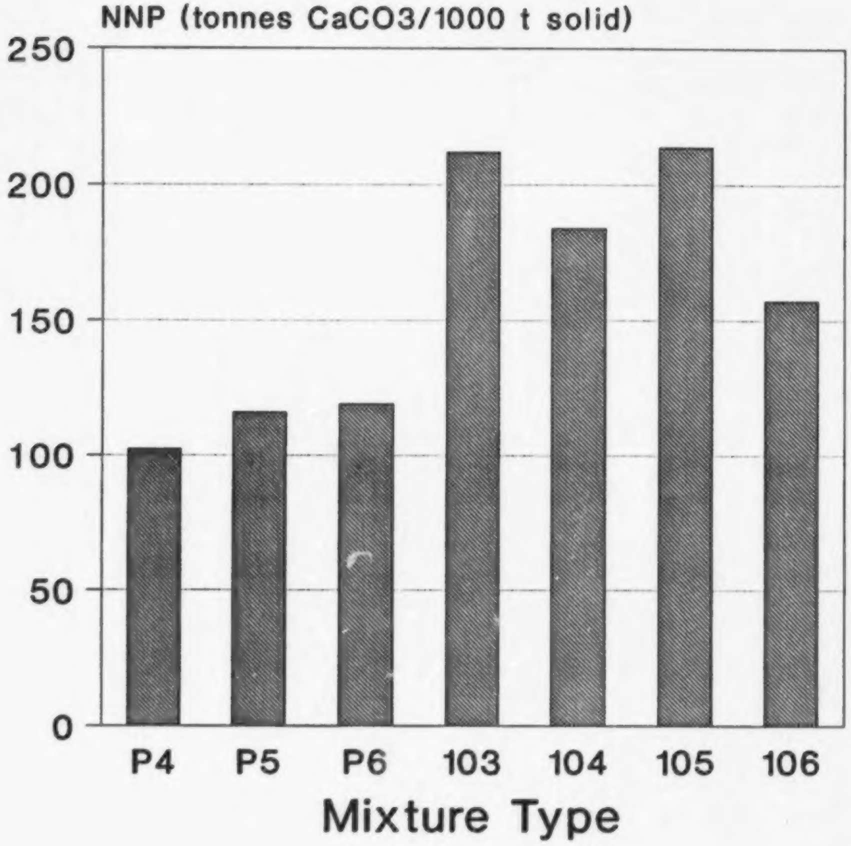
Figure 5.19 shows the Net Neutralization Potential (NNP) of cementitious mixtures containing 18 to 25 percent cement and various other components such as fly ash, sludge, sand and coarse tailings. Values in the range of -20 to +20 tonne $CaCO_3$/1000 tonnes solid are considered to have potential to generate net acidity (AMD Technical Guide, 1989). The results show that all test mixtures have NNP's greater than +20 tonne $CaCO_3$/1000 tonnes solid. The NNP is obviously higher for mixtures containing larger quantities of cement and lower with increased amounts of tailings in the as shown by mixtures 103 and P6. Therefore, the cement content used in the mixtures more than adequately neutralizes the potential acidity of the mine tailings.

The leaching data for the test mixtures, summarized in Figures A1-A21 in the Appendix, suggest that mixtures can be prepared to meet the Federal and Provincial discharge limitations and the B.C. Special Waste Regulation leaching criteria. Levels of aluminum occasionally exceed the B.C. Effluent criteria for Special Waste Facilities, however the criteria are not considered of direct relevance to the intended application.

5.3.7 Cost Comparison

Cement is often the most costly component of cementitious mixtures. Supplementary cementing materials such as fly ash, sludge or hydrated lime can be used to lower the amount of cement required to achieve solidified cementitious mixtures with equivalent properties to mixtures with higher cement contents. Therefore, using material costs as a constant factor, physical properties of test mixtures containing various quantities of cement and supplementary cementing materials were evaluated (Table 5.4).

Figure 5.19
Net Neutralization Potential of Cementitious Mixtures



MIXTURE COMPOSITION (%)

P4: 18 cement/10 fly ash/ 72 coarse tails/additives

P5: 22 cement/9 sludge/ 69 coarse tails/additives

P6: 25 cement/75 coarse tails/ additives

103: 25 cement/15 sand/ 60 coarse tails/additives

104: 25 cement/5 sand/ 70 coarse tails/additives

105: 25 cement/10 sand/ 65 coarse tails/additives

106: 20 cement/10 sand/ 70 coarse tails/additives

Mixtures 82 to 87 were prepared to compare properties of various mixtures with similar material costs. Costs per m^2 assume a 10 cm thick layer of sealant. The results shown in Table 5.4 indicate that replacing a portion of the cement content of a mixture with fly ash (mixture 83 and 90) produced a solid sample with comparable physical properties to mixtures with higher cement contents (mixture 82 and 93). However, the handling cost of an additional component and the lack of improvement in the physical properties of the fly ash mixtures does not warrant their inclusion in the cementitious mixtures.

Replacement of a significant portion of cement with lime (mixture 84) produced a mixture with lower strength than the equivalent cost cement and coarse tailings mixture. Lowering the lime content to 0.7% improved the strength of the cementitious mixture, but the handling cost of an item used to replace less than 1% of the cement cannot be justified. Addition of 7% sludge (0.7% dry weight) produced a cementitious mixture with comparable compressive strength to mixture 82 containing only cement and coarse tailings, however the initial set time was significantly retarded. Therefore, the process could be used as a means for disposal for sludge where a longer initial set time can be tolerated.

The material costs of solidified mixtures which would effectively serve the purpose as durable surface sealants are in the order of $4.10 to $6.20 per square meter. The cost of application will be based on the results of future studies.

Material costs for optimal surface sealants such as high density polyethylene (Nilex 80) are in the order $9.50/$m^2$ (Northwest Geochem 1988 cost for test pile liners). Till covers, of which at least one meter depth is required, cost in the order of $14.25 per square meter[1] (Mount Washington experience 1989, personal communication M. Galbraith).

Therefore, the solidified tailings mixture approach may offer a competitive, cost-effective control for sealing of the waste rock dumps.

---

[1] Based on 1 m depth; 5 km adverse haul from borrow site; compacted to an average modified proctor of 95%; separation of boulders not required; no watering required to obtain compaction; placed on 3:1 slope.

Table 5.4: Cost Comparison of Mixtures Containing Supplementary Cementing Materials

Mix No.	Composition	Initial Set (h)	Compression Strength 7 Day	Compression Strength 28 Day	Material Cost
82	15 cement/85 coarse tails/additives	7	--	19.5	\$4.12/m^2 \$41.20/m^3
83	11 cement/7 fly ash/82 coarse tails/additives	6	--	19.2	\$4.12/m^2 \$41.20/m^3
84	12 cement/6 lime/82 coarse tails/additives	7	--	13	\$4.12/m^2 \$41.20/m^3
86	14 cement/0.7 lime/85.3 coarse tails/additives	8	14.8	21.9	\$4.06/m^2 \$40.58/m^3
87	14 cement/7 sludge/85.3 coarse tails/additives	15	11.1	19.1	\$4.06/m^2 \$40.58/m^3
90	18 cement/10 fly ash/72 coarse tails/additives	7	16.5	26	\$5.78/m^2 \$57.82/m^3
93	25 cement/75 coarse tails/additives	7	22.2	29	\$6.18/m^2 \$61.79/^{3}

6.0 FIELD STUDIES

6.1 Procedures

Six test piles of waste rock were placed on individual high density polyethylene membranes. The size of each test pile was approximately 5 m x 5 m x 2 m (height). The test piles were prepared during the fall of 1987 and runoff waters from each were collected at intervals for analyses. Measurements of pH and runoff volume were continuous and recorded on a remote recording device.

Three solidification test mixtures were applied to individual test piles during the fall of 1988, and another three were applied during the summer of 1989. Five cubic yards of each selected test mixture were prepared by means of either mixing the ingredients at a concrete ready mix facility in Campbell River with delivery to the site by cement truck, or by loading the cement mixer truck with ingredients at the mine site.

The 1988 mixtures were pumped onto the pile surface by means of a pumper truck hose (Plate 1). Distribution was completed manually using shovels. Compression test cubes and Vicat cones were prepared in the field for determination of compression strength and setting times, respectively. Field measurements conducted during 1989 also included air content and slump tests. In each case the base of the solidified mixtures was trowelled to enable the collection of surface runoff waters for pH measurements and for water quality assessment.

6.2 Results

The prepared mixtures were easily pumped and applied to the rock surface. All test mixtures showed the ability to stick to and set on the vertical surfaces of the waste rock piles.

Table 6.1 describes the mixtures, their current status and selected physical properties.

PLATE 1

Application of Surface Sealant Mixture

Table 6.1: Results of Field Testing Program

Application Date	Pile #	Composition (% weight)	Initial Set Time (h)	Compression Strength (MPa)*	Status February (1990)
Nov. 1988	2	Cement: 10 Sand: 20 Fine Tailings: 70	24	4.1	Freeze thaw effects after 4 months.
Nov. 1988	3	Cement: 8.5 Coarse Tailings: 91.5	28	2.9	Still intact. $CaSO_4$ crystals on surface.
Nov. 1988	4	Cement: 8 Sludge: 16 Sand: 39 Coarse Tailings: 37	18	11	Turned 'powdery' after 5 months. (due to application problems)
Aug. 1989	4C	Cement: 18 Flyash: 10 Coarse Tailings: 72 Admixtures	7	29.8	Fine cracks after 5 hours. Still intact.
Aug. 1989	5	Cement: 22 Sludge: 9 Coarse Tailings: 69 Admixtures	6	22.6	Fine cracks after 5 hours. Still intact.
Aug. 1989	6	Cement: 25 Coarse Tailings: 75 Admixtures	7	23	Fine cracks after 5 hours. Still intact.

* at 28 days

6.2.1 Structural Integrity

Severe winter conditions with temperatures to -20 degrees Celsius followed the application of three mixtures in November 1988. The mixture (pile 2) with 10% cement, 20% sand and 70% fine tailings cracked extensively after 4 months as a result of freeze-thaw effects. The mixture consisting of 8% cement, 16% sludge, 39% sand and 37% coarse tailings turned "powdery" after 5 months probably a result of problems which occurred during the application process. Due to an ambient temperature near 0°C during application, a propane heater was used to maintain higher temperatures within the covered test pile and it is suspected that proper hydration reactions did not occur within the mixture. The 8.5% cement and 91.5% coarse tailings mixture on pile 3 remains in good condition as of February 1990.

Following extensive laboratory testing to optimize the solidification mixtures, three more mixtures were placed on separate piles during August 1989. Despite excellent performance of the mixtures on a laboratory scale the field scale trials were not entirely successful. Within a five hour period all mixtures on the piles developed fine cracks. Subsequent efforts to duplicate this cracking in laboratory tests were unsuccessful, (i.e., 1" x 24" and 18" x 24" molds of duplicate test mixtures showed no evidence of shrinkage or cracking).

Consultation with technical representatives from W.R. Grace Ltd., LaFarge Cement and Tilbury Cement, and with materials engineers at Powertech Labs Inc. (previously B.C. Hydro Research), suggested that the cracking was caused by one or both of the following factors:

Heat of Hydration

The materials used in the mixtures are representative of a mortar rather than a concrete mix. Mortar mixes consist of cement and sand while concrete contains larger sized aggregate. A larger quantity of cement paste is necessary in a mortar mix because of the correspondingly larger amount of particle surface area. The larger quantity of cement will generate a high heat of hydration causing the solid mixture to crack. Hydration can be simply explained as the chemical reaction which takes place between cement and water as portland cement mixtures cure, while the heat of hydration is the amount of heat released as the cement cures.

In a large mass of concrete, heat is not rapidly dissipated and a significant rise in temperature can occur causing thermal expansion and subsequent cracking as the mass of concrete undergoes nonuniform cooling. Differential settlement of the fresh concrete mixture during placement likely contributed to non-uniform cooling.

Therefore, excessive heat of hydration maybe responsible for the cracking observed in the field scale applications (Powertech Labs., 1990 personal communications). Extrapolation of laboratory data obtained from test mixtures prepared in 2 inch cube forms is difficult when compared with the large amount of cement mix applied to the waste rock piles. Hence, problems such as excessive heat of hydration were not noted in the test mixtures prepared in the laboratory. Similar problems were not encountered during the 1988 field tests which used lower quantities of cement.

Particle Size Distribution

It was the view of technical personnel from cement companies that the uniformity of particle size and the density of the tailings may have resulted in a high degree of bleeding (physical water loss) from the mixture. This may have caused incomplete hydration of the cementitious material and the "collapse" of the structural integrity of the solidification mixture during field application.

A solution to both possible causes of the observed cracking would be addition of a graded coarse aggregate containing a proportion of gravel sized material, to enable a varying particle size distribution. In other words, the mixture would no longer be a "mortar mix". If the heat of hydration hypothesis is correct, lower cement contents should also be used. Further field studies (e.g. 1/3 cu. yd. quantities) will be required to resolve this issue.

6.2.2 Chemical Integrity of Solidified Mixtures

Mixtures P4, P5 and P6 shown in Figure 5.19 indicate that the solidified mixtures selected for the 1989 field studies had net neutralization potentials (NNP) ranging from 100 to 210 tonnes $CaCO_3$/1000 tonnes solid. The NNP levels are more than adequate to assure the absence of oxidation of the sulfur content in the tailings component of the solidified mixture (AMD Technical Guide, 1989).

Table 6.2 provides an overview of the chemical characteristics of surface runoff waters from four of the existing test piles. Analyses of runoff waters prior to placing the covers, shows that active oxidation was occurring within the waste rock with pHs of runoff waters ranging from 2.7 to 4.7.

Following placement of the solidified mixtures on the waste rock piles, monitoring of runoff waters was representative of leachates from the cementitious covers. The pH values ranged from 6.5 to 10.3. Assuming that a waste rock pile is successfully treated with such covers, the runoff waters would approximate the post-cover water quality observed in Table 6.2. If soil is placed on the cover as part of a reclamation program then a less alkaline pH could be expected.

Table 6.2 indicates that metal releases are minimal with aluminum concentrations from 2.5 to 10 times lower than the B.C. Special Waste criteria level of 0.2 ppm and copper concentrations from 40 to 200 times lower than the WMB discharge limit of 0.2 ppm.

The data also show that the laboratory acid leach test generally overestimates metal releases (Table A-3), when compared to field leaching data. The only exception is aluminum where field releases were slightly higher from test piles 4 and 5 (0.05 and 0.06 mg/L) than levels found in laboratory leachate studies (0.02 mg/L, Table A-3).

To this date, the chemical integrity of the solidified mixtures covering the test piles appears satisfactory.

6.3 Future Studies

Brief field trials are required to resolve the issue of cracking as discussed in Section 6.2.1. Subsequently, engineering approaches for application would be pursued. Shotcreting is the preferred means for surface application of the cementitious mixtures because it can be applied in difficult places and over large areas. In the past five years, research in cement technology has focused on the development of a high flexural-tensile strength and low drying shrinkage for shotcreted materials (Powertech, 1989). Flexural strength is a measure of the solid material's ability to withstand local settlement and reduces the incidence of cracking. These are important properties for the long-term use of the material as a surface sealant.

Table 6.2
PRE AND POST COVER
WESTMIN TEST PILE DATA
(mg/L)

PRE-COVER Parameter*	pH	Acidity	Sulfate	Ca	Mg	Al	Cd	Cu	Fe	Pb	Ni	Zn
TP 1												
Aug.18/88	2.8	830	1620	86	1.2	1.7	0.5	5.4	1.5	0.4	0.18	10.9
Nov.02/88	3.1	172	471	74	3.7	2.8	0.1	5.2	2.1	0.3	0.05	13.4
TP 2												
Aug.18/88	3.5	401	1400	80	1.1	1.9	0.3	4.9	0.8	0.9	0.14	10.6
Nov.02/88	4.2	127	666									
TP 3												
Aug.18/88	3.2	1454	3400	117	0.94	1.6	1.1	5.6	3	1	0.74	7
Nov.02/88	3.9	276	1084									
TP 4												
Aug.18/88	3.0	575	1410	58	0.88	1.3	0.2	3.8	1.5	0.2	0.099	8.2
Nov.02/88	4.7	276	432									
TP 5												
Aug.18/88	3.0	977	2220									
TP 6												
June 28/89	2.7	2551	4490	54	45	4.9	0.53	6.6	21.9	0.43	0.085	4.6
POST-COVER												
TP 3												
Nov/88-Aug/89	6.5-8.2											
Nov.28/89	9.4			5.2	0.06	0.034	0.0003	0.0008	0.004	0.0004	0.0008	0.0007
TP 4												
Nov.28/89	10.2			2.9	0.05	0.024	L 0.0003	L 0.0008	L 0.004	0.0004	L 0.0008	0.002
Jan.05/90	9.8			3.6	0.05	0.070	L 0.0020	L 0.0050	0.013	L 0.02	L 0.0050	L 0.002
TP 5												
Nov.28/89	10.4			2.7	0.06	0.046	L 0.0001	L 0.0008	L 0.004	0.0008	L 0.0008	0.007
Jan.05/90	9.9			3.2	0.05	0.050	L 0.0020	L 0.0050	0.178	L 0.02	L 0.0050	L 0.002
TP 6												
Nov.28/89	10.3			2.0	0.03	0.027	L 0.0003	L 0.0008	L 0.004	0.0007	L 0.0008	L 0.0007
Jan.05/90	9.9			3.4	0.05	0.080	L 0.0020	L 0.0050	0.007	L 0.02	L 0.0050	L 0.002

In addition, materials laboratories have worked on enhancing concrete flexibility as part of efforts to "earthquake proof" all concrete structures (Powertech, 1989). It is the intent that such technology would be applied to future components of this study.

7.0 GROUTING

Grouting can be defined as the injection of or placement of appropriate materials into soils, rocks or man-made structures to seal voids and thereby reduce permeability and/or increase strength (Bowen, 1981). Although grouting practice is a well defined technology for use in soils and geological formations, a lack of objective criteria exist for assessing grout characteristics in materials with heterogeneous void spaces as represented by the Westmin waste rock dump which contains materials ranging from clay sized to boulders. In general, desirable grout characteristics for subsidence and drainage control include: mixture flowability, cohesiveness (ability to maintain a consistent solid-liquid matrix), strength and durability.

There are zones of net acid generation at depth in the Westmin waste rock dump based on acid-base accounting analyses. These zones are sometimes informally referred to as "hot spots" of acid generation. Application of grout to these zones could effectively control the acid generation process by sealing the "hot spot" so that neither oxygen nor water can reach the acid generating rock. Cement slurries are one of the most widely used grouting materials. However, grout used to seal large void spaces commonly contains aggregate in addition to cement to increase the viscosity of the grout. Use of a cement containing grouting material to seal voids at depth in the Westmin waste rock dump would also provide a measure of alkalinity to neutralize potential acidity.

In order to assess the use of a solidified mixture composed of cement, mine tailings and sand as a grouting medium and to demonstrate the capability to seal cobble to boulder sized void spaces a pilot scale test was conducted in which a test grout mixture was applied to three small rock enclosures.

Rock enclosures were constructed by placing large rock fragments (approximately 18-22 cm diameter) in gabion boxes measuring 1 x 1 meter. Grout was introduced through an 8 cm diameter PVC pipe installed in the center of the rock enclosure. The rationale for using an open ended system such as this was to more closely simulate both the continuity and the 3-dimensional nature of voids in a waste rock dump. In addition, the flowability of the grout through the rock voids can easily be assessed.

For a preliminary assessment on the use of a solidified mixture as a grouting medium it was decided to evaluate only one solid mixture at varying water contents. Mixture #103 composed of 25% cement, 60% tailings, 15% sand and air entrainment and strengthening additives was chosen on the basis of its high cement content, low shrinkage and high compressive strength. In addition, this mixture has not shown the tendency to crack, even when poured in large molds (23 cm x 55 cm).

The water:cement content was varied in three separate mixtures to determine the optimum flowing characteristics of the grout without causing excessive bleeding and thereby affecting the cohesiveness of the mixture and reducing the compressive strength.

The results (shown below) indicated that the grout characteristics varied significantly over a narrow range of water:cement content. The first mixture contained 56% water:cement and was found to bleed more than 10% by the time of initial set. This mixture was not poured into the rock enclosure. A 49% water:cement ratio was used for the second mixture. The mixture did not bleed and it was possible to feed the mixture down the PVC tube, however, it would not flow adequately into the void spaces. The third mixture had a water:cement ratio of 53% and was to satisfy all the requirements for a desirable grouting material to fill large void spaces.

The grout materials were poured into molds and cured in a humidity chamber for subsequent testing. Freeze/thaw testing was carried out on the grout mixture after the 28-day curing period.

Mixture #103

water:cement Ratio	Initial Set	Final Set	% Bleeding	Compressive Strength
0.56	6 h	~ 20 h	>10%	--
0.49	5 h	~ 15 h	<2%	--
0.53	5 h	13 h	2%	19.5 MPa

To date the grout materials have performed well in the rock enclosures (i.e., cracking has not been observed, shrinkage appears to be minimal). Freeze/thaw testing of the grout mixture has successfully completed 15 cycles.

8.0 SUMMARY AND CONCLUSION

This report documents the results of a program to evaluate acid generation and hydrogeology of the Westmin Myra Falls waste rock dump and to evaluate novel approaches for preventing acid mine drainage from waste rock dumps.

Acid-base accounting of 230 borehole samples obtained during the waste rock dump study, showed that the most active areas of oxidation occur within a 10 meter depth of exposed surfaces of the waste rock dump and in deeper zones where relatively high contents of sulfide minerals are located. Water moving through the waste rock dump originates from infiltration of precipitation and lateral groundwater discharge from the valley wall. During periods of significant rainfall, the shallow acid-generating zones are flushed with water and acidic water appears beneath the water table. However, general calculations suggest that a significant portion of the annual production of acidity is retained in the dump and therefore remains available for flushing. As a result, remediation and decommissioning planning must address the neutralization of this acidity or the control of infiltration and water-table variation.

Various approaches to preventing acid mine drainage at the Westmin site were considered and two were selected for evaluation: bactericidal application and control of air and water by sealing the waste rock dump surface and/or by grouting specific regions of the dump.

Initial efforts to evaluate the bactericidal approach were stopped upon the availability of the results from the waste rock dump characterization which indicated that acid generation control at depth would be required. Bactericidal approaches have been shown to be effective only at surface or shallow depths. The most promising control approach was the development of a cementitious solidification mixture incorporating mine waste materials for use as a waste rock dump surface sealant and grouting matrix. Mine waste water sludge and mine tailings were used as principal components of the solidification mixtures, and solidified materials could be prepared at less than costs associated with other surface sealants such as high density polyethylene liners. Other components of the mixture include cement, sand, wastewater sludge and small quantities of commercial admixtures. The solidified materials have similar properties to that of construction concrete in terms of compression strengths, setting times, workability and durability as measured by freeze/thaw testing. Field and laboratory leaching studies and acid-base accounting of the cementitious materials, indicate the materials are chemically stable.

In addition to optimizing the cementitious mixtures by varying mix proportions, this study also evaluated the influence of material properties, such as particle size distribution, and the addition of admixtures and supplementary cementing materials on physical and chemical properties of the mixtures. Field scale tests indicated that particle size distribution, in particular, has a significant influence on the use of tailings as a major component.

Five mixtures of the solidification have been applied on waste rock test piles. The applications are under regular observation with samples of runoff water obtained for pH and metal assessment. To date, 4 of the 5 test piles have retained their physical and chemical integrity. The applications show that this approach has considerable compatibility with future reclamation efforts. The solidification mixtures have also been tested for use as grouting materials, and to date the pilot scale test results are encouraging.

The tests indicate that mixtures of similar composition could be used either for surface application or for grouting with the only variable being water content. Verification of the best candidate mixture is dependent upon future pilot scale field tests. It is, therefore, intended that the next phase of study would evaluate engineering approaches for application of the cementitious mixture as a surface cover, in particular by use of shotcreting. The approaches would simultaneously consider latest technology in enhancing flexural strength to withstand potential problems associated with local settlement.

REFERENCES

American Public Health Association, American Water Works Association, Water Pollution Control Federation. 1985. Standard Methods for Examination of Water and Wastewater, 16th Edition, Washington, D.C.

Bell, A.V. 1987. Prevention of acid generation in base metal tailings and waste rock. In Acid Mine Drainage Seminar Workshop. 23-26 March 1987, Halifax, Nova Scotia. Environment Canada. 1987. Draft.

Bowen, R. 1981. Grouting in Engineering Practice. John Wiley & sons, New York.

B.C. AMD Task Force. 1989. AMD Technical Guide, Vol.1. Prepared by SRK. Norecol Environmental Consultants and Gormely Process Engineers.

B.C. Research. 1981. Water Quality In The Thelwood And Myra Creek Drainages; Phase I.

B.C. Research. 1982a. Water Quality In The Thelwood And Myra Creek Drainages; Interim Report.

B.C. Research. 1982b. Phase II Monitoring (Hydrology, Water Quality, Groundwater) At The Buttle Lake Site, Westmin Resources Ltd. Operations, Volumes I and II.

B.C. Research. 1983. Phase III Monitoring Of Surface Water Quality In The Myra Creek Drainages.

Caruccio, F.T., T.C. Ferm, J. Horne, G. Geidel and B. Baganz, 1977. Paleoenvironment of coal and its relation to drainage quality. U.S. Environmental Protection Agency Report EPA-600/7-71-067, p. 108.

Caruccio, F.T., and G. Geidel. 1987. The in-situ mitigation of acidic drainages - management of hydro-geochemical factors. In Acid Mine Drainage Workshop Seminar. 23-26 March 1987, Halifax, Nova Scotia. Environment Canada. Draft.

CCREM. 1987. Canadian Water Quality Guidelines. Prepared by the Task Force on Water Quality Guidelines of the Canadian Council of Resource and Environment Ministers. Environment Canada.

CPCA. 1984. Design and Control of Concrete Mixtures. Canadian Portland Cement Association, Ottawa, Ontario.

EPA. 1986. Handbook for Stablization/Solidification of Hazardous Waste. NTIS PB87-116745.

Erickson, P.M., R.L.P. Kleinmann and S.J. Onysko. 1985. Control of acid mine drainage by application of bactericidal materials. In Control of Acid Mine Drainage, Proceedings of a Technology Transfer Seminar. U.S. Dept. of the Interior. Bureau of Mines Information Circular 9027. Pittsburgh, PA.

Errington, J.C. and K.D. Ferguson. 1987. Acid Drainage in British Columbia. Today and Tomorrow. In: Proc. Acid Drainage Seminar/Workshop, March 1987, Halifax, Nova Scotia, p. 67-87.

Hope, B.B., and V.M. Malhorta. 1984. The measurement of concrete permeability. Can. J. Civil. Eng. 11: 287-292.

Imai, K., T. Sugio, T. Tsuchida and T. Tano. 1975. Effect of heavy metal ions on the growth and iron-oxidizing activity of Thiobacillus ferrooxidans. Agr. Biol. Chem. 39(7):1349-1354.

Jones, C.E. 1982. Stage II Reclamation Studies for the Westmin Mine Development. Prepared for Westmin Resources Ltd.

Kleinmann, R.L.P. and P.M. Erickson. 1983. Control of acid drainage from coal refuse using anionic surfactants. Report of Investigations 8847. U.S. Dept. of the Interior, Bureau of Mines.

Klusman, R.W. and S. Machemer. 1989. Modelling of geochemical processes occurring in a constructed wetland used to treat acid mine drainage. Presented at the 1989 International Chemical Congress of Pacific Basin Society, Honolulu, Hawaii, December 17-22, 1989.

Knight and Piesold Ltd. 1982. Myra Falls: Tailings Disposal Facility, Volume 1, Main Report.

Knight and Piesold Ltd. 1989. Myra Falls: Interim Report On Hydrogeologic Assessment Of Waste Dump.

Ladwig, K.J., P.M. Erickson, and R.L.P. Kleinmann. 1985. Alkaline injection: an overview of recent work. In Control of Acid Mine Drainage, Proceedings of a Technology Transfer Seminar. U.S. Dept of the Interior. Bureau of Mines Information Circular 9027. Pittsburgh, PA.

McCready, R.G. 1987. A review of the physical/chemical/biological measures to prevent acid mine drainage: an application to the pyritic Halifax shales. In Acid Mine Drainage Seminar Workshop. 23-26 March 1987, Halifax, Nova Scotia. Environment Canada. Draft.

McLellan, J.E. and P.L. Coté. 1988. Guide for Selection of Leaching Tests. Draft report.

Northwest Geochem. 1988. Study of Methods to Control Acid Generation on Waste Rock. Submitted to the Acid Drainage Task Force of the Mineral Development Agreement Assistance Program.

Northwest Geochem. 1990. A Critical Review Of Waste Rock Information. MEND Report.

Patterson, R. 1984. Evaluation of sodium lauryl sulphate as a media to control acid mine drainage. Equity Silver Mines Ltd. Internal Report.

Patterson, R. 1987. Environmental and reclamation measures at Equity Silver Mines Limited. In Acid Mine Drainage Seminar Workshop. 23-26 March 1987, Halifax, Nova Scotia. Environment Canada. Draft.

SIMCO Groundwater Research Ltd. 1983. Groundwater Study In Relation To The Elevated Metal Concentrations In Myra Creek.

Sobek, A.A. 1987. The use of surfactants to prevent acid mine drainage in coal refuse and base metal tailings, pp. 357-390. In Proceedings of the Acid Mine Drainage Seminar Workshop, Halifax, Nova Scotia, 23-26 March 1987.

Stewart, J. (Savolite Chemicals, Delta, B.C.). 1987. Personal communication.

Tuovinen, O.H., S.I. Niemela and H.G. Gyllenbuerg. 1971. Tolerance of Thiobacillus ferrooxidans to some metals. Antonie van Leeuwenhoek 37:489-496.

APPENDIX

TABLE A-1
WESTMIN AMD CONTROL MIXTURES

MIX #	PERCENT COMPOSITION
2	30 cement/70 sludge
3	20 cement/80 sludge
4	10 cement/90 sludge
5	5 cement/95 sludge
6	2.5 cement/97.5 sludge
7	1 cement/99 sludge
8	10 cement/89 sludge
9	5 cement/94 sludge/1 NaCl
10	20 cement/50 sludge/30 shale
11	10 cement/60 sludge/30 shale
12	5 cement/65 sludge/30 shale
13	5 cement/75 sludge/20 shale
14	2 cement/78 sludge/20 shale
15	2 cement/88 sludge/10 shale
23	100 cement
26	1.5 cement/5.5 sludge/3 shale/ 90 coarse tails
27	4.5 cement/16.5 sludge/9 shale/70 coarse tails
28	8 cement/27 sludge/15 shale/50 coarse tails
29	10 cement/38 sludge/22 shale/30 coarse tails
30	13 cement/50 sludge/27 shale/10 coarse tails
31	15 cement/55 sludge/30 shale
32	15 cement/55 sludge/30 shale
33	15 cement/55 sludge/30 shale
34	6 cement/22 sludge/24 sand/48 coarse tails
35	8 cement/20 sludge/24 sand/48 coarse tails
36	6 cement/15 sludge/18 sand/61 coarse tails
37	6 cement/22 sludge/24 sand/48 coarse tails
38	6 cement/22 sludge/24 sand/48 coarse tails

39	6 cement/22 sludge/24 sand/48 coarse tails
40	6 cement/15 sludge/18 sand/61 coarse tails
41	6 cement/15 sludge/18 sand/61 coarse tails
42	6 cement/47 sand/47 coarse tails
43	6 cement/94 coarse tails
44	6 cement/20 sand/74 coarse tails
45	6 cement/15 sludge/18 sand/61 coarse tails
P2A	10 cement/20 sand/70 coarse tails
P4A	8 cement/16 sludge/ 39 sand/37 coarse tails
46	15 cement/10 sludge/15 sand/60 coarse tails
47	10 cement/15 sludge/15 sand/60 coarse tails
48	10 cement/15 sludge/15 sand/60 coarse tails
49	10 cement/90 fine tails
50	10 cement/90 fine tails
51	10 *cement/90 fine tails
52	10 cement/20 sand/70 fine tails
53	8.5 cement/91.5 coarse tails
54	5.9 cement/21.7 sludge/24.4 sand/48 coarse tails
55	10 cement/20 sand/70 fine tails
56	8.5 cement/91.5 coarse tails
57	5.9 cement/21.7 sludge/24.4 sand/48 coarse tails
58	3 cement/97 coarse tails
59	5 cement/95 coarse tails
60	7 cement/93 coarse tails
61	10 cement/90 coarse tails
62	15 cement/85 coarse tails
63	20 cement/80 coarse tails
64	10 cement/90 coarse tails
65	10 cement/90 coarse tails
66	10 cement/90 coarse tails
67	10 cement/10 lime/30 sand/50 coarse tails
68	10 cement/5 lime/35 sand/50 coarse tails
69	10 cement/10 fly ash/80 coarse tails

70	10 cement/90 coarse tails/Daravair(DV)**
71	10 cement/90 coarse tails/Daracem(DC)**
72	10 cement/85 coarse tails/5 (Force 10,000)
73	10 cement/90 coarse tails/DV,DC
74	10 cement/10 fine tails/80 coarse tails/DV,DC
75	10 cement/10 sand/80 coarse tails/DV,DC
76	10 cement/7 Na_2SiO_3/83 coarse tails/DV,DC
77	10 cement/90 coarse tails/Microair,Rheobild
78	5.9 cement/2.6 lime/30.5 sand/61 coarse tails
79	11 cement/89 coarse tails/DV,DC
80	12 cement/88 coarse tails/DV,DC
81	13 cement/87 coarse tails/DV,DC
82	15 cement/85 coarse tails/DV,DC
83	11 cement/7 fly ash/82 coarse tails/DV,DC
84	21 cement/6 lime/82 coarse tails/DV,DC
85	13 *cement/87 coarse tails/DV,DC
86	14 cement/0.7 lime/85.3 coarse tails/DV,DC
87	14 cement/7 sludge/85.3 coarse tails/DV,DC
88	15 cement/10 sand/75 coarse tails/DV,DC
89	15 cement/10 fine tails/75 coarse tails/DV,DC
90	18 cement/10 fly ash/72 coarse tails/DV,DC
91	18 cement/82 coarse tails/DV,DC
92	20 cement/80 coarse tails/DV,DC
93	25 cement/75 coarse tails/DV,DC
P4C	18 cement/10 fly ash/72 coarse tails/DV,DC
P5	22 cement/9 sludge/69 coarse tails/DV,DC
P6	25 cement/75 coarse tails/DV,DC
94	25 cement/75 coarse tails
95	25 cement/75 coarse tails
96	25 cement/75 coarse tails/DV,DC
97	25 cement/75 coarse tails/DC
98	25 cement/75 coarse tails/DV
99	25 cement/75 coarse tails/DV,DC

100	25 cement/75 coarse tails/DV,DC
101	25 cement/75 coarse tails
102	25 cement/75 coarse tails/DV,DC
103	25 cement/15 sand/60 coarse tails/DV,DC
104	25 cement/5 sand/70 coarse tails/DV,DC
105	25 cement/10 sand/65 coarse tails/DV,DC
106	20 cement/10 sand/70 coarse tails/DV,DC

* sulfate resistant cement

** Daravair (DV) = air entrainment agent
Daracem (DC) = strengthening agent

Table A-2. Physical Properties of Cementitious Mixtures

#	Water/Cement Ratio	Initial Set(h)	Final Set(h)	Shrinkage (linear,%)	Strength 7-day	Strength 28-day	Water Permeability (cm/s)	Freeze/Thaw # Cycles	Freeze/Thaw Integrity
2		14	43				1.1E-06		
3		48	168				1.1E-06		
4		38	290				1.4E-06		
5		30	480				2.4E-06		
6		120	960				1.4E-06		
7		168	960				2.1E-07		
8		26	245				8.1E-07		
9		38	480				3.9E-06		
10		10	22				5.3E-05		
11		17	90				4.0E-06		
12		17	186				4.8E-06		
13		18	312				3.8E-06		
14		48	384				1.9E-06		
15		90	504				1.5E-06		
23									
26		24	120	2					
27		15	66	2			7.5E-07		
28		12	72	2			1.9E-06		
29		14	60	2			1.8E-06		
30		13	140	2			2.2E-07		
31		15	140	2.5					
32		18	140	2.5			4.1E-07		
33		20	140	-					
34		30	42	2					
35		30	40	2	7.0(14-day)		3.6E-07	12	okay
36		40	72	2			9.7E-07		
37		24	114	2			1.4E-06		
38		40	152	2					
39		24	186	3.3			5.3E-05		
40		32	108	2			6.3E-06		
41		19	84	2			3.1E-06		
42		24	72	2			4.9E-06		
43		48	96	2			5.3E-06		
44		24	72	2			4.4E-06	12	okay
45		48	408	2					
P2A				2			6.3E-07	11	
P4A				2			9.8E-07		
46	0.83	6	18	2	1.31 (14-day)		9.0E-06		
47	0.92	7	24	2	7.06 (14-day)		3.0E-07		
48	0.80	17	30	2	6.87 (14-day)		1.1E-06		
49	0.52	24	~41	2	3.94 (14-day)		8.9E-07		
50	0.51	24	~41	2	4.14 (14-day)				
51	0.58	24	~40	2	4.4 (14-day)				
52	0.64	~24	~36	1		4.14/3.14			
53	0.76	~28	~40	1		3.01/2.75			
54	no data	~18	~64	1		1.68/1.59			
55	0.67	24	~33	2					
56	0.69	28	~32	2				26	failed
57	no data	18	~32	2					
58	0.76	~24	~44			0.7			
59	0.69	~18	~33			2.8			
60	0.64	~14	~32			5.47			
61	0.58	~12	~20			10.7			

Mix #	Water/Cement Ratio	Initial Set(h)	Final Set(h)	Shrinkage (linear,%)	Strength 7-day	Strength 28-day	Water Permeability (cm/s)	Freeze/Thaw # Cycles	Freeze/Thaw Integrity
62	0.62	~10	~18			21.3			
63	0.56	~8	~16			30.9			
64	0.67	~8	~16			8.28			
65	0.63	~10	~18			9.03			
66	0.73	~13	~22			5.38			
67	0.56	~4	~17	2		8.76		24	failed
68	0.59	~4.5	~24	2		11		39	okay
69	0.44	~9	~17	2		13.2/13.6		36	cracks formed
70	0.51	~7	~22	2		10.3/11		36	cracks formed
71	0.47	~9	~24	2		12.5/9.84		36	cracks formed
72	0.50	~7	~22	2		29.2/27.4		36	slight spalling
73	0.42	~8	~21	2		11.6/11.3	2.1E-06	36	okay
74	0.39	~6	~22	2		15.5/15.1		32	cracked & spalling
75	0.46	~7	~23	2		15.2/13.9		30	slight spalling
76	0.43	~3.5	~8	2		10.1		30	long crack formed
77	0.45	~6	~23	2		10.7/11.7		28	okay
78	0.65	~5.5	~23	2		6.78/6.02		28	strong spalling
79	0.47	~7	~24	2		11.8/10.9		25	okay
80	0.47	~6	~23	2		10.3/10.5		25	slight spalling
81	0.42	~4.5	~21	2		15.4/16		25	slight spalling
82	0.42	~7	~24	2		19.1/19.9		25	slight spalling
83	0.39	~6	~22	2		19.1/19.3		25	slight spalling
84	0.42	~7	~8.5	2		13.5/12.5		25	okay
85	0.44			2		13.4/12.8		25	okay
86	0.43	~8	15	<1	14.8	21.5/22.2		20	okay
87	0.49	~15	~23	<1	11.1	15/19.1		20	okay
88	0.60	~8	~24	<1	8.92	13.8/13.9		20	slight spalling
89	0.60	~7	~23	<1	7.71	16.1/15.4		20	slight spalling
90	0.46	7	~22	<1	16.5	25.4/26.5		20	slight spalling
91	0.58	7	<24	<1	11.3	19.4/18.4		20	slight spalling
92	0.56	7	<24	<1	12.3	20.6/19.5		20	slight spalling
93	0.49	7	<24	<1	22.2	29.8/28.5		20	okay
P4C	-	7	<24	shrunk	22	29.8		15	okay
P5	-	-	-	shrunk	17.1	22.6		15	okay
P6	-	-	-	shrunk	19.6	23/23.4		15	cracks formed
94	0.57	-	-	none	20.5	30.7/28		-	-
95	0.53	-	-	none	20.6	24.2/26.5		-	-
96	0.53	13	29	none	27.9	28.9/24.9		-	-
97	0.54	13	29	none	30.8	24.7/27.9		-	-
98	0.56	11	21	none	17.8	19.3/18.8		-	-
99	0.53	11	21	0.7	14.4	23/22.9		-	-
100	0.57	11	21	0.7	15.9	28.7/30		15	okay
101	0.58	11	21	0.7	17.3	24.9/23.9		-	-
102	0.51	-	-	1				-	-
103	0.48	-	-	0.3	23.7	34.7/35.4	**3.21E-10	15	okay
104	0.50	>7	-	0.9	23.9			15	okay
105	0.50	>7	-	1	23.4			15	okay
106	0.57	>7	-	0.9	14.2			-	-

** Water permeability test conducted by Powertech Labs.

Table A-3. Metal Levels in Leachate (mg/L)

Mix #	Final pH	Al	As	Ca	Cd	Cr	Cu	Fe	Mg	Na	Ni	Pb	Zn
2	12.0	0.198	0.0001	780.1	0.003	0.195	0.037	4	0.088	5.785	0.174	0.0062	0.11
3	11.8	0.971	0.0001	298	0.0033	0.488	0.0333	0.9038	0.029	3.348	0.0417	0.0007	0.0264
4	11.8	1.516	0.0001	323.6	0.002	0.152	0.026	1.258	0.031	2.86	0.0431	0.0008	0.0564
5	11.0	1.865	0.0032	185.3	0.0022	0.167	0.0465	0.755	0.298	2.269	0.0173	0.0003	0.1208
6	10.1	1.446	0.0114	140.5	0.0011	0.0619	0.0084	0.131	0.464	0.851	0.0074	0.0009	0.0155
7	8.2	0.222	0.0017	168.8	0.0011	0.0231	0.0084	0.299	6.587	0.805	0.0081	0.0009	0.0174
8	11.5	2.729	-	217.7	0.0011	0.0661	0.0475	0.0282	0.0165	3.513	0.0194	0.0027	0.0347
9	10.8	3.515	-	156.7	0.0023	0.1535	0.3646	0.0282	0.192	8.086	0.0507	0.0009	0.0291
10	12.0	0.518	0.0002	344.4	0.0011	0.0607	0.0315	0.38	0.0258	2.668	0.0246	0.0014	0.0222
11	11.7	1.629	0.0061	203.9	0.0011	0.0877	0.0138	0.246	0.028	1.483	0.0168	0.0009	0.0284
12	10.8	1.84	0.0050	149.3	0.0011	0.1031	0.0084	0.233	0.145	1.308	0.0096	0.0009	0.018
13	10.0	0.533	0.0143	143.8	0.0011	0.0966	0.0084	0.216	1.532	1.677	0.0091	0.0009	0.019
14	7.7	0.726	0.0058	152.8	0.0011	0.0403	0.0084	0.38	14.323	1.131	0.0138	0.0009	0.0432
15	7.5	0.519	0.0036	181.4	0.0011	0.0411	0.0084	0.527	16.168	1.127	0.0138	0.0009	0.0752
23	12.2	1.334	0.0001	456.4	0.0003	0.1332	0.0087	0.302	0.0709	13.365	0.1199	0.0002	0.0076
26	5.5	0.572	0.0001	315	0.0072	0.0700	1.285	1.091	16.647	2.923	0.1291	1.203	14.925
27	5.7	0.509	0.0001	415.4	0.002	0.0745	0.562	1.013	13.097	5.874	0.1786	0.173	5.024
28	10.0	10.633	0.0048	657.5	0.0015	0.2068	0.0343	0.869	9.268	8.533	0.2418	0.0172	0.168
29	11.3	4.191	0.0001	282.2	0.0005	0.1077	0.0086	0.372	0.797	6.489	0.1276	0.0066	0.134
30	11.6	2.563	0.0001	235.1	0.0001	0.0718	0.0092	0.241	0.305	7.126	0.0862	0.0024	0.0327
31	11.9	4.975	0.0001	555.8	0.0005	0.2156	0.2	0.469	0.263	13.907	0.1632	0.0006	0.0156
32	11.6	3.272	0.0001	295.5	0.0004	0.1691	0.0104	0.263	0.476	11.363	0.1059	0.0004	0.0296
34	11.0	0.676	0.0022	139.6	0.001	0.0497	0.0118	0.533	0.915	0.8456	0.0211	0.0057	0.03
35	11.3	1.944	0.00002	289.8	0.0017	0.1023	0.0005	1.441	0.414	2.095	0.0585	0.0031	0.0393
36	10.2	0.325	0.0077	186.1	0.001	0.0313	0.0005	0.77	2.547	1.527	0.0266	0.0005	0.0201
37	9.4	0.169	0.0131	248.1	0.0009	0.0450	0.0005	0.995	4.887	2.060	0.0379	0.0001	0.038
38	8.3	0.085	0.0002	484.5	0.0022	L 0.0006	0.0184	1.44	9.761	2.305	0.1253	0.0001	0.1472
39	9.0	0.298	0.0047	484.6	0.0018	L 0.0006	0.0236	1.452	8.992	3.017	0.1044	0.0003	0.1125
40	8.9	0.476	0.00002	645.3	0.0042	L 0.0006	0.043	2.347	11.146	2.979	0.1673	0.0009	0.2035
41	10.5	1.017	0.0023	319.3	0.0017	0.0293	0.0005	1.653	2.008	1.964	0.0506	0.0005	0.0623
42	8.4	0.001	0.0053	755.8	0.0047	L 0.0006	0.2339	2.391	15.128	4.54	0.1691	0.0015	0.2537
43	8.3	0.001	0.0104	562.7	0.0044	L 0.0006	0.109	1.908	12.015	2.628	0.1555	0.0014	0.363
44	8.0	0.001	0.0088	572.7	0.0035	L 0.0006	0.0678	1.71	10.74	3.09	0.117	0.0008	0.4418
45	7.9	0.001	0.00002	803.6	0.0065	L 0.0006	0.2163	2.586	22.005	5.165	0.1776	0.0013	0.9391
P2A	10.2	0.188	0.0067	318	0.0005		0.0128	0.992	1.37			0.0029	0.0291
P4A	11.2												
46	11.4	0.523	0.00019	218	0.00025	0.0126	0.0021	0.121	0.351	3.16	0.0025	0.00337	0.0017
47	10.8	1.19	0.00951	143	0.00036	0.0095	0.00464	0.226	0.381	7.49	0.0042	0.00239	0.0366
48	11.4	1.05	0.0116	319	0.00016	0.0469	0.0073	0.437	0.182	8.53	0.0223	0.00619	0.0501
49	8.0	0.0779	0.0136	406	0.00087	0.0008	0.047	0.267	3.33	5.95	L 0.0017	0.0063	0.0522
50	9.2	0.334	0.0138	330	0.00034	0.0054	0.01	0.29	0.655	8.15	L 0.0006	0.00457	0.26
51	9.4	0.0921	0.0148	355	0.00057	0.0015	0.00794	0.263	0.588	5.2	L 0.0017	0.00347	0.185
55	7.7	0.0703	0.00224	239	0.00018	L 0.0004	0.00539	0.013	0.615	0.248	0.0006	0.00222	0.151
56	11.1	0.446	0.00049	94.8	0.00009	0.0009	0.00628	0.0018	0.099	0.177	L 0.0004	0.001	0.00287
57	10.1	0.525	0.004226	97.1	0.00009	0.0005	0.0066	0.0242	0.536	0.176	L 0.0004	0.00142	0.0136

Mix #	Final pH	Al	As	Ca	Cd	Cr	Cu	Fe	Mg	Na	Ni	Pb	Zn
67	11.9	0.199	0.00869	114	0.00017	0.0035	0.00084	0.0182	0.0258	1.21	0.0026	0.0104	0.00058
68	11.3	0.27	0.00675	126	0.0001	0.0062	0.0007	0.0339	0.166	2.8	0.00378	0.00118	0.00158
69	7.6	0.131	0.0169	64	0.00011	L 0.0005	0.00084	0.00226	0.0979	2.31	L 0.00043	0.00033	0.00348
70	10.4	0.516	0.00499	62.9	0.00011	L 0.0005	0.00454	0.0643	0.0703	1.33	L 0.00043	0.00292	0.00562
71	10.0	0.512	0.00989	53.2	0.00011	L 0.0005	0.00446	0.0719	0.0593	1.69	L 0.00043	0.00353	0.0148
72	5.0	0.0613	0.00811	48	0.00011	L 0.0005	0.00583	0.0898	0.0661	1.02	L 0.00043	0.00808	0.0582
73	10.9	0.604	0.00155	56.2	0.00011	L 0.0005	0.0024	0.0381	0.449	1.76	L 0.00043	0.00163	0.00304
74	10.6	0.239	0.0106	27.8	0.00009	L 0.0004	0.00748	0.0251	0.0179	1.47	L 0.00036	0.00146	0.00781
75	10.7	0.695	0.00393	20.8	0.00005	L 0.0004	0.00494	0.0494	0.00834	1.55	L 0.00036	0.00385	0.00574
76	10.1	0.129	0.0322	9.52	0.00006	0.0023	0.0732	0.557	0.0302	1.51	0.00176	0.0034	0.00896
77	7.7	0.0628	0.00801	31.3	0.00044	L 0.00025	0.0148	0.0562	0.151	0.647	0.00054	0.00108	0.00928
78	10.6	0.426	0.00104	33.6	0.00013	0.0004	0.0028	0.0209	0.271	0.478	0.00068	0.00062	0.00115
79	11.0	0.839	L 0.00018	72.9	0.00008	L 0.0009	0.0054	0.0227	0.249	8.1	0.00104	L 0.00032	L 0.00114
80	11.0	0.574	L 0.00018	52.5	0.00008	L 0.0009	0.00096	0.0237	0.156	8.43	0.0005	L 0.00032	L 0.00114
81	11.1	0.563	L 0.00018	77.2	0.00008	L 0.0009	0.00568	0.0345	0.161	9.05	L 0.0004	0.00189	0.00329
82	11.2	0.594	L 0.00018	73.4	0.00008	L 0.0009	0.00683	0.0189	0.221	9	L 0.0004	0.00054	L 0.00114
83	10.9	0.920	0.00636	69.5	0.00008	L 0.0009	0.00367	0.0168	0.375	10.4	L 0.0004	L 0.00032	L 0.00114
84	11.1	0.571	0.0002	133	0.00008	L 0.0009	0.00559	0.0228	0.423	10.1	L 0.0004	0.00894	L 0.00114
85	11.2	0.371	0.0174	123	0.00008	L 0.0009	0.0127	0.102	0.289	10.1	0.0017	0.00735	L 0.00109
86	11.8	0.248	L 0.00018	225	0.00017	0.0014	0.00405	0.0565	0.0716	1.42	0.00295	0.00611	0.00398
87	11.7	0.399	L 0.00018	766	0.00007	L 0.0003	0.00398	0.0535	0.15	0.911	0.00047	0.00196	0.0134
88	11.1	0.670	L 0.00018	101	0.00008	0.0004	0.00718	0.134	0.136	1.116	0.00156	0.00707	0.0376
89	11.3	0.391	L 0.00018	148	0.00055	0.0032	0.00342	0.0619	0.094	1.64	0.00202	0.00185	0.0198
90	11.3	1.08	L 0.00018	111	0.00019	L 0.0003	0.00248	0.078	0.0898	1.78	0.00159	0.00156	0.0164
91	11.3	0.93	L 0.00009	91	L 0.00008	L 0.0004	0.00306	0.0304	0.0746	1.13	0.00066	L 0.00035	0.00251
92	11.6	0.406	L 0.00009	121	L 0.00008	L 0.0004	0.00044	0.0264	0.0365	1.32	0.00165	0.00279	0.00081
93	11.6	0.55	L 0.00009	104	0.00013	L 0.0004	0.00128	0.0405	0.0559	1.48	0.00093	0.00199	0.00626
P4C	10.3	0.0236	L 0.00002	319	0.00096	0.1030	0.0156	0.0761	21.8	3.27	0.0378	0.00862	0.0192
P5	11.2	0.0249	0.00644	294	0.00049	0.0569	0.0178	0.0579	15.1	1.8	0.0358	0.00798	0.0118
P6	11.7	0.247	L 0.00002	153	L 0.00005	L 0.0009	0.00593	0.0281	0.0422	0.943	L 0.00037		
100	11.4	0.258	L 0.00002	337	0.00033	0.135	0.0223	0.124	0.258	2.31	0.0484	0.00616	0.0196
Effluent Criteria Level:		0.2	1.0		0.005		0.2	0.3				0.05	0.5

AMD CONTROL MIXTURES

ALUMINUM LEACHATE

Criteria Level = 0.2 ppm

Figure A-1

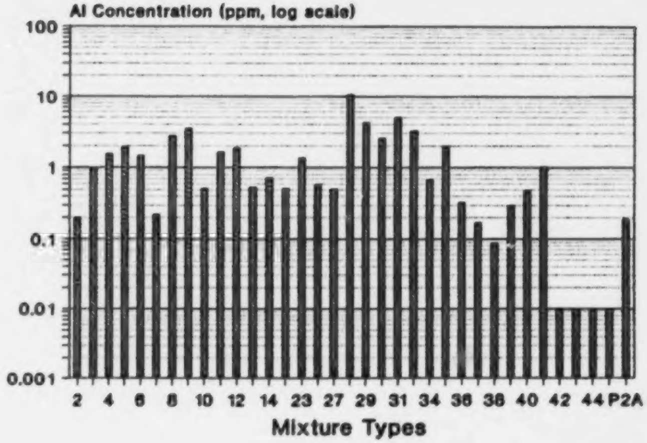


Figure A-2

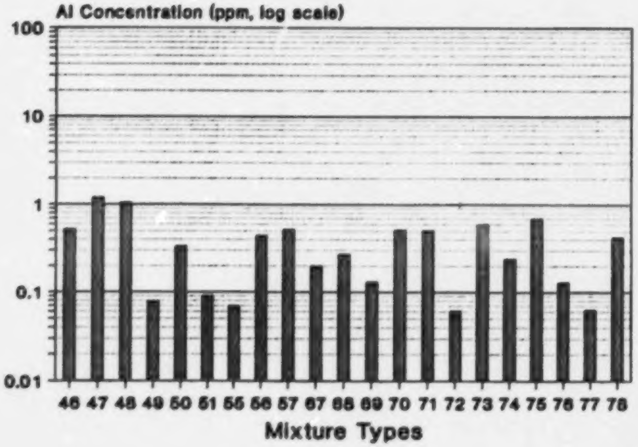
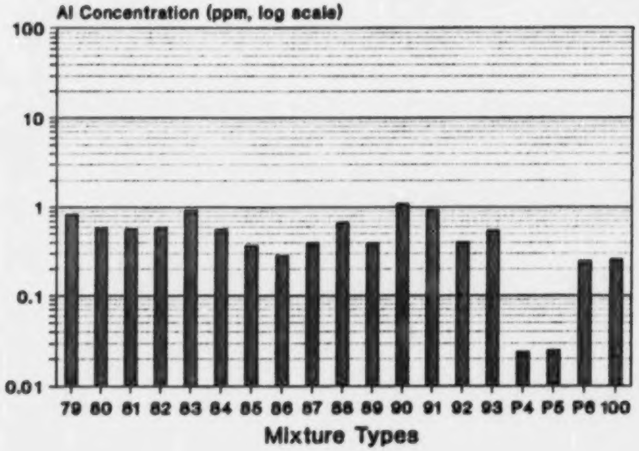


Figure A-3



AMD CONTROL MIXTURES

ARSENIC LEACHATE

Criteria Level = 1.0 ppm

Figure A-4

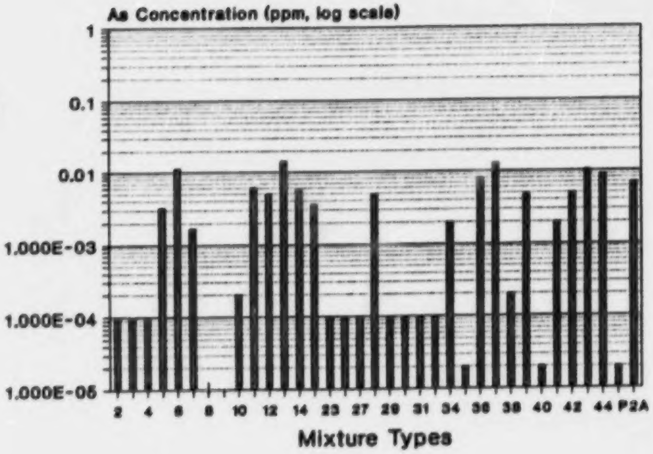


Figure A-5

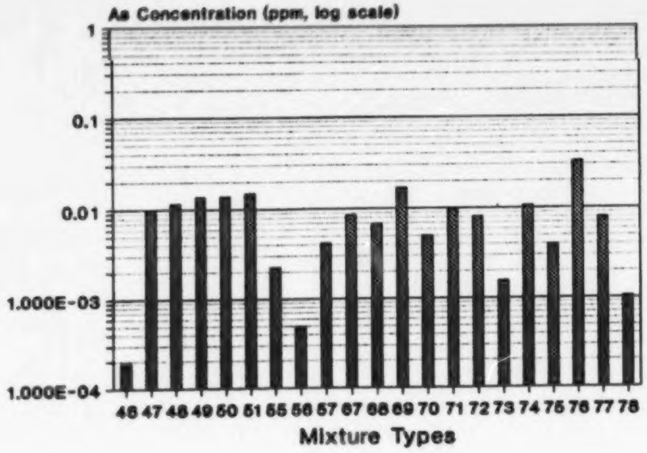
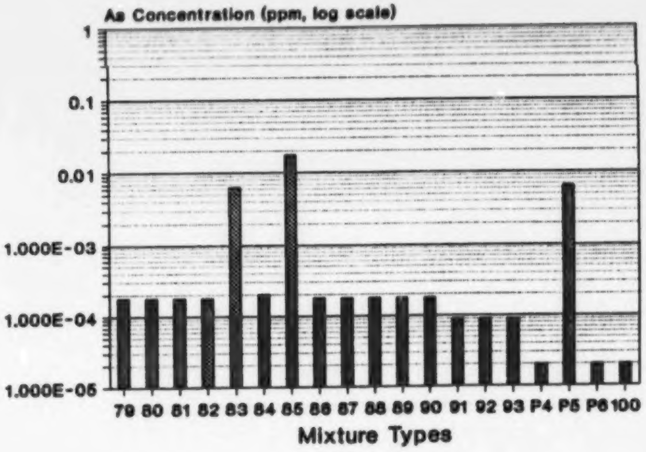


Figure A-6



AMD CONTROL MIXTURES

CADMIUM LEACHATE

Criteria Level = 0.005 ppm

Figure A-7

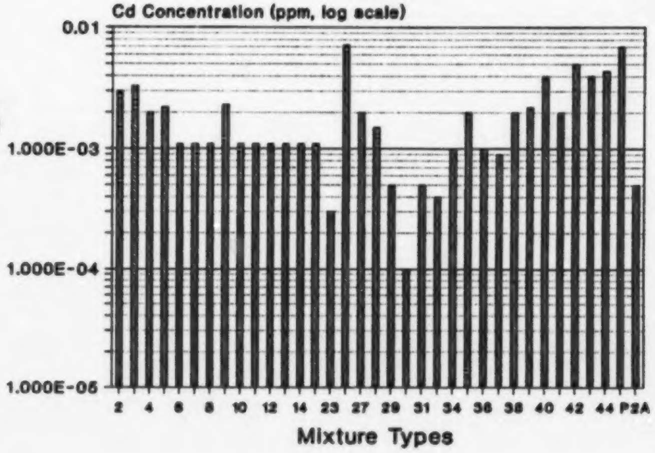


Figure A-8

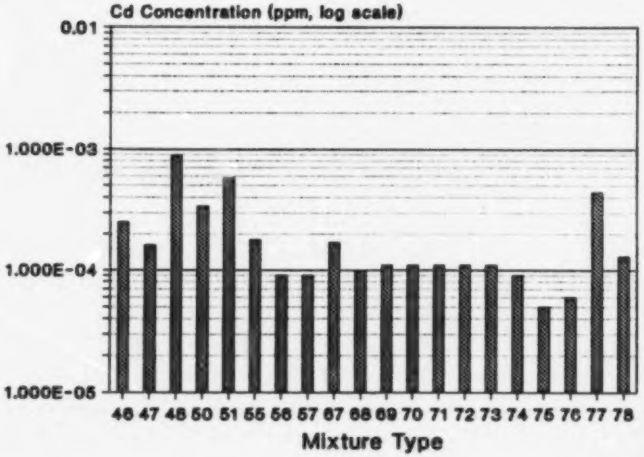
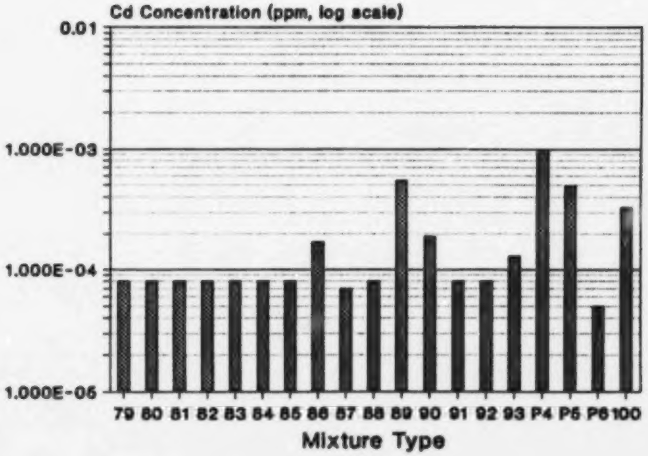


Figure A-9



AMD CONTROL MIXTURES

COPPER LEACHATE

Criteria Level = 0.2 ppm

Figure A-10

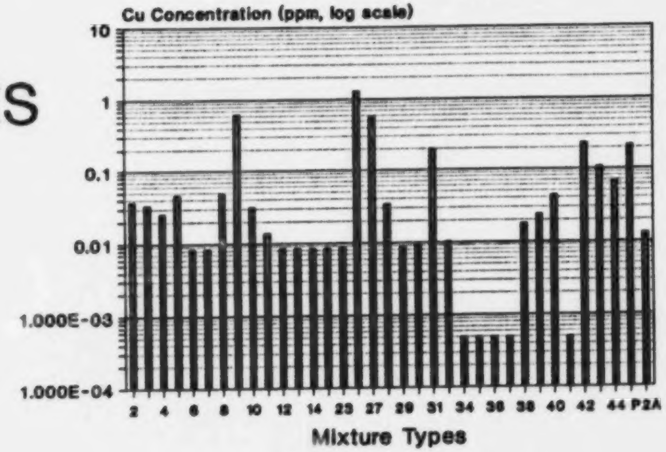


Figure A-11

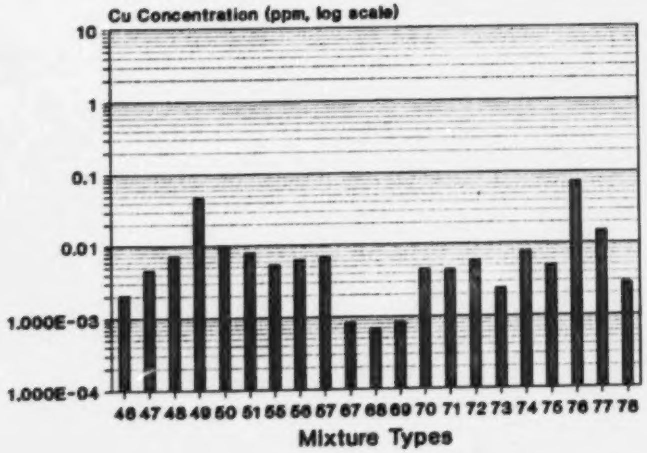
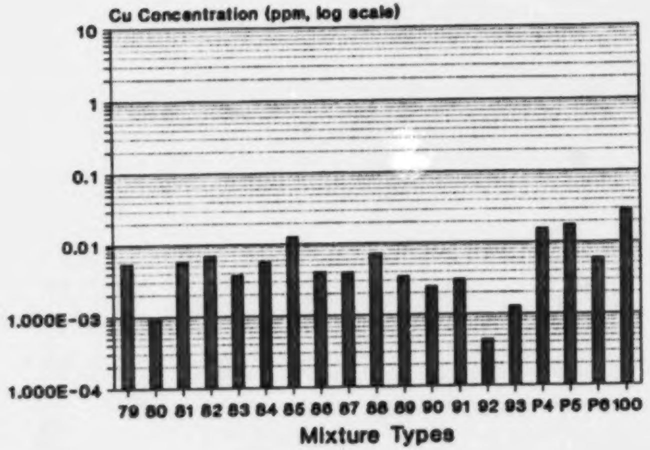


Figure A-12



AMD CONTROL MIXTURES

IRON LEACHATE

Criteria Level = 0.3 ppm

Figure A-13

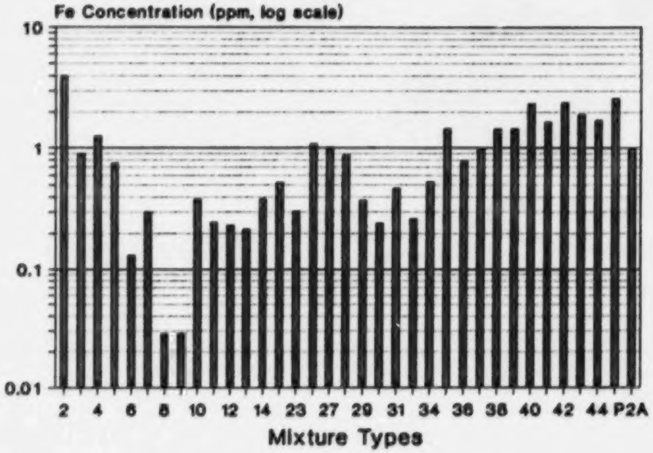


Figure A-14

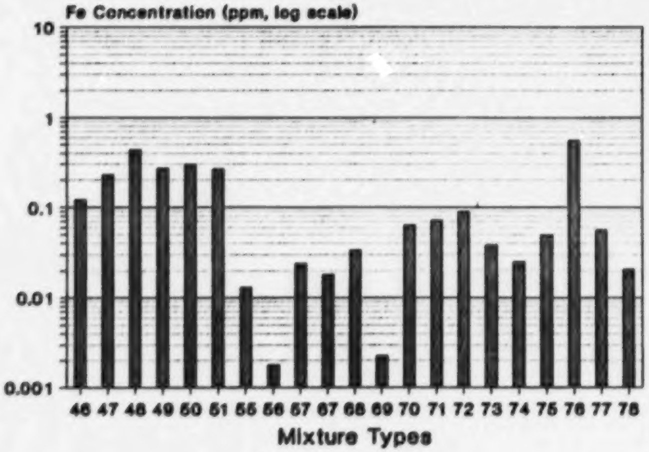
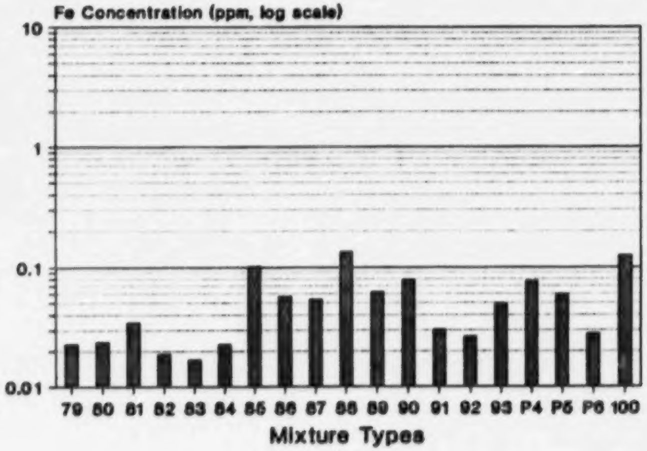


Figure A-15



AMD CONTROL MIXTURES
LEAD LEACHATE

Criteria Level = 0.05 ppm

Figure A-16

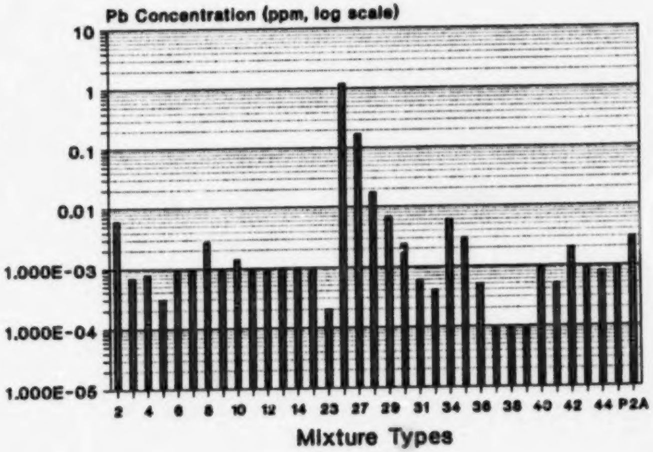


Figure A-17

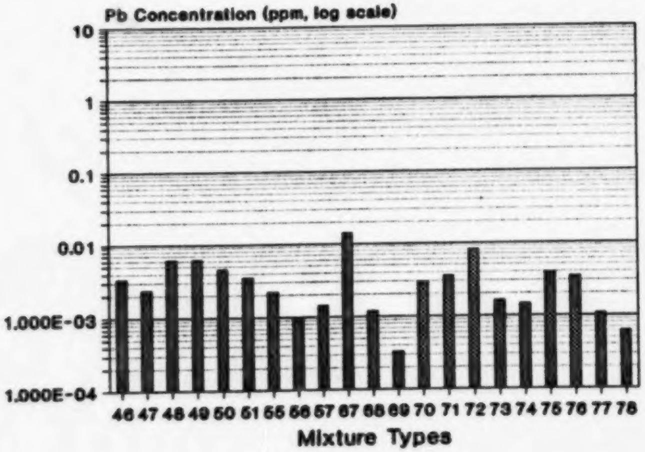
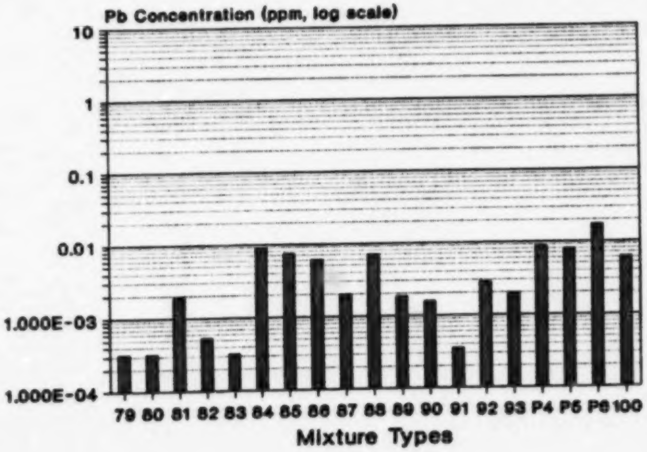


Figure A-18



AMD CONTROL MIXTURES

ZINC LEACHATE

Criteria Level = 0.5 ppm

Figure A-19

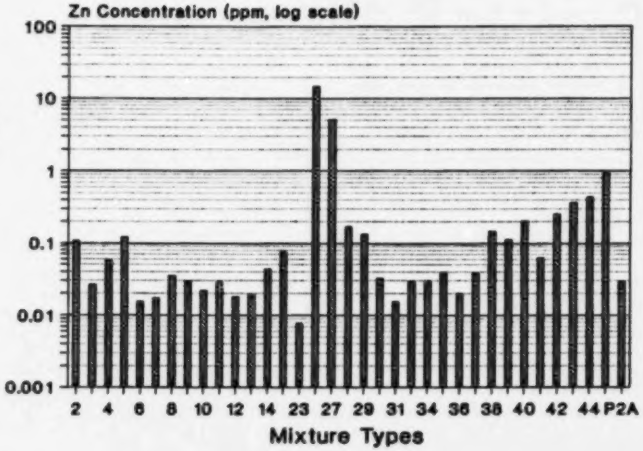


Figure A-20

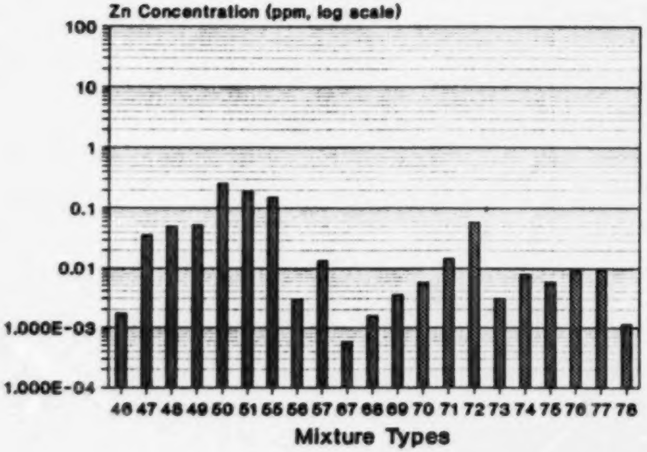
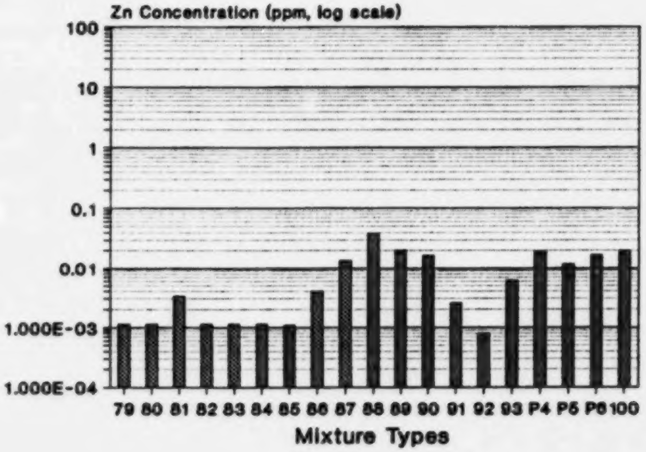


Figure A-21



Waste Management Branch
Permit PE-6582 for Myra Pond Outflow

Metal	Dissolved	Total
Zinc	0.5 mg/L	1.0 mg/L
Copper	0.2 mg/L	0.6 mg/L
Cadmium	0.005 mg/L	--
Lead	0.05 mg/L	--

pH 6.5 - 11.0

- -

Environment Canada
Metal Mining Liquid Effluent Regulations and Guidelines

Schedule I
Part I
Objective for Substances

Substance	Column I Maximum acceptable monthly arithmetic mean concentration	Column II Maximum acceptable concentration in a composite sample	Column III Maximum acceptable concentration in a grab sample
Arsenic	0.5 mg/L	0.75 mg/L	1.0 mg/L
Copper	0.3 mg/L	0.45 mg/L	0.6 mg/L
Lead	0.2 mg/L	0.3 mg/L	0.4 mg/L
Nickel	0.5 mg/L	0.75 mg/L	1.0 mg/L
Zinc	0.5 mg/L	0.75 mg/L	1.0 mg/L

British Columbia
Waste Management Act
Special Waste Regulation

- excerpts of effluent and leachate criteria

SCHEDULE 1

[am. B.C. Reg. 10/89, s. 11.]

EFFLUENT CRITERIA FOR SPECIAL WASTE FACILITIES

Parameter	Maximum Concentration or Range (in (mg/ℓ) unless otherwise specified)
Physical	
pH	6.5 to 8.5*
Temperature	32°C
Total suspended solids	20
Toxicity (Limit bioassay)	100% effluent
Inorganics	
Aluminum, dissolved	0.2
Ammonia, dissolved (expressed as nitrogen)	1.0
Antimony, dissolved	0.25
Arsenic, dissolved	0.1
Barium, dissolved	1.0
Boron, dissolved	10.0
Cadmium, dissolved	0.1
Chromium, dissolved (hexavalent)	0.1
Chromium, total	0.5
Cobalt, dissolved	0.1
Copper, dissolved	0.1
Cyanide (weak acid dissociable)	0.1
Fluoride, dissolved	15
Lead, dissolved	0.1
Manganese, dissolved	0.1
Mercury, total	0.001
Molybdenum, dissolved	0.5
Nickel, dissolved	0.5
Selenium, dissolved	0.05
Tin, dissolved	0.5
Zinc, dissolved	0.2
Organics	
5 day Biochemical oxygen demand	20
Oil	10
Phenol	0.2
Polychlorinated biphenyls, total	0.005
Polychlorinated dibenzofurans, total	30 ng/ℓ
Polychlorinated dibenzo-p-dioxins, total	30 ng/ℓ
Total organic halogens	1.0

*pH units are the negative log of the hydrogen ion concentration

Table 1: Leachate Quality Criteria

[am. B.C. Reg. 10/89, s. 12.]

Item	Column I Contaminant	Column II Concentration in Waste Extract (mg/ℓ)
1.	2, 4, 5-TP /Silvex / 2-(2, 4, 5 -Trichlorophenoxy) propionic acid	1.0
2.	2, 4 -D	10.0
3.	Aldrin + Dieldrin	0.07
4.	Arsenic	5.0
5.	Barium	100.0
6.	Boron	500.00
7.	Cadmium	0.5
8.	Carbaryl / 1-Naphthyl-N-methyl carbamate /Sevin	7.0
9.	Chlordane	0.7
10.	Chromium	5.0
11.	Cyanide (free)	20.0
12.	DDT	3.0
13.	Diazinon/Phosphordithioic acid, 0,0-diethyl 0-(2- isopropyl 6-methyl-4-pyrimidinyl) ester	0.02
14.	Endrin	0.02
15.	Fluorides	150.0
16.	Heptachlor + Heptachlor epoxide	0.3
17.	Lead	5.0
18.	Lindane	0.4
19.	Mercury	0.1
20.	Methoxychlor/1, 1, 1-Trichloro-2, 2-bis (p-methoxyphenyl) ethane	10.0
21.	Methyl Parathion	0.7
22.	Nitrate + Nitrite	1 000.0
23.	Nitrilotriacetic acid	5.0
24.	Nitrite	100.0
25.	***Repealed.*** [B.C. Reg. 10/89, s. 12.]	
26.	Parathion	3.5
27.	Selenium	1.0
28.	Silver	5.0
29.	Toxaphene	0.5
30.	Trihalomethanes	35.0
31.	Uranium	2.0